

Aerosols, Clouds, and Climate

Michael D. King

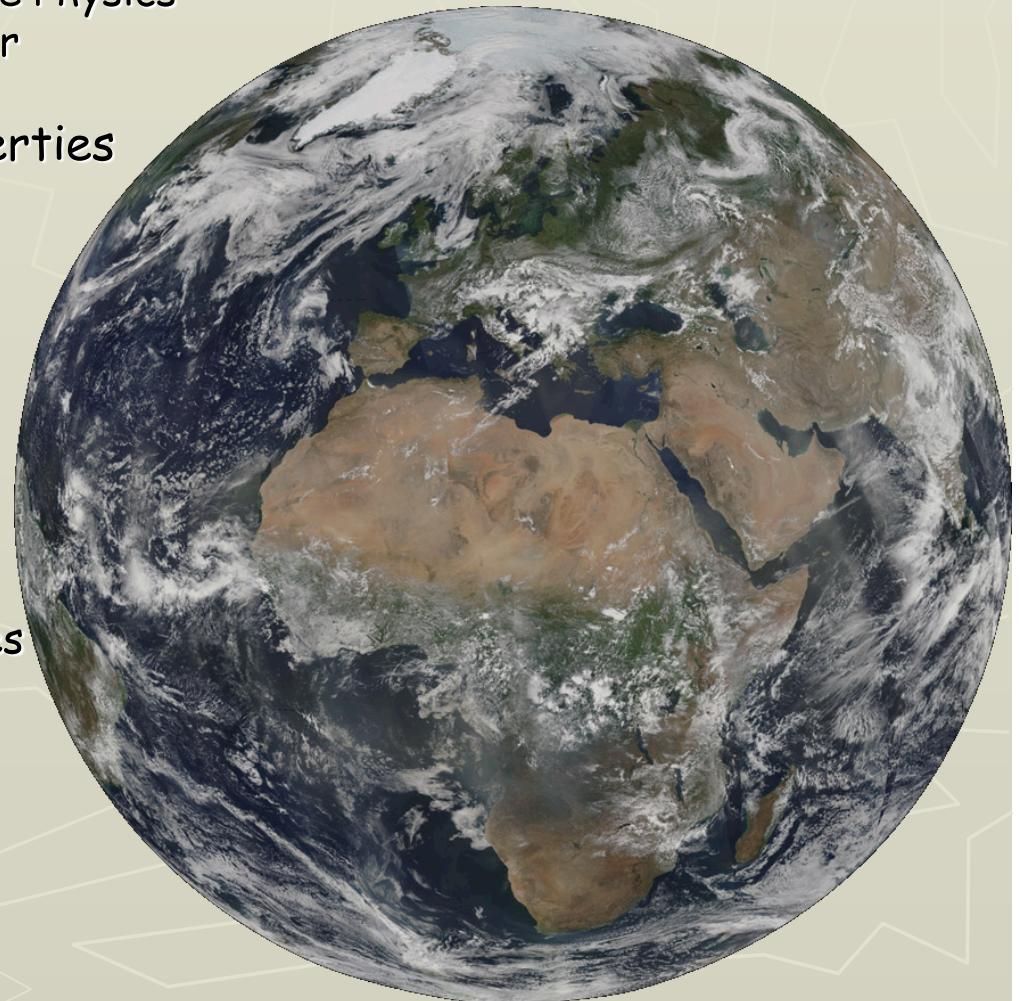
Laboratory for Atmospheric and Space Physics
University of Colorado-Boulder

➤ Aerosol optical & microphysical properties

- Satellite remote sensing
 - ✓ Dense dark vegetation
 - ✓ Bright-reflecting surfaces
 - ✓ MODIS/MISR aerosol over land
 - ✓ Long-range transport
 - ✓ Air quality applications

➤ Cloud properties

- Cloud fraction
- Cloud optical & microphysical properties
- Land surface albedo
 - ✓ Snow-free and snow-covered
- Cloud statistical properties
- Ship tracks



MODIS Aerosol Products

- Eight MODIS bands are utilized to derive aerosol properties
 - 0.41, 0.47, 0.55, 0.66, 0.86, 1.24, 1.64, and 2.13 μm
 - Ocean
 - ✓ reflectance contrast between cloud-free atmosphere and ocean reflectance (dark)
 - ✓ aerosol optical thickness (0.55-2.13 μm)
 - ✓ size distribution characteristics (fraction of aerosol optical thickness in the fine particle mode; effective radius)
 - Land
 - ✓ dense dark vegetation and semi-arid regions determined where aerosol is most transparent (2.13 μm)
 - ✓ contrast between Earth-atmosphere reflectance and that for dense dark vegetation surface (0.47 and 0.66 μm)
 - ✓ aerosol optical thickness (0.47 and 0.66 μm)
 - ✓ fraction of aerosol optical thickness in the fine particle mode
 - ✓ Deep blue algorithm for bright reflecting surfaces uses 0.41, 0.47, and 0.66 μm (**implemented in February 2007**)

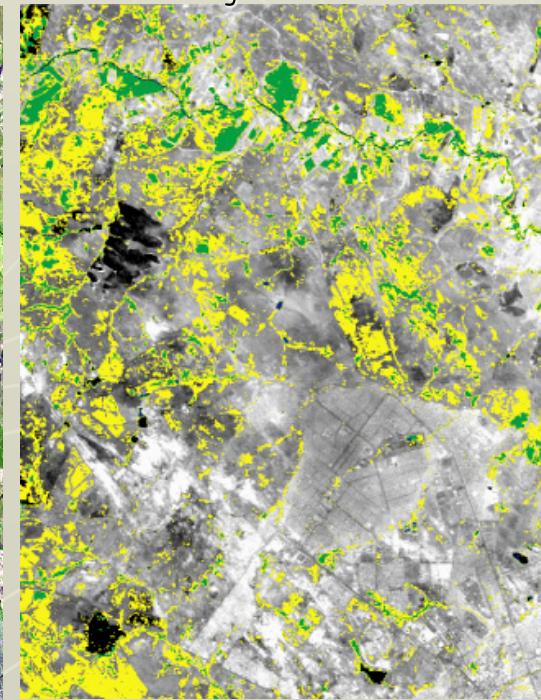
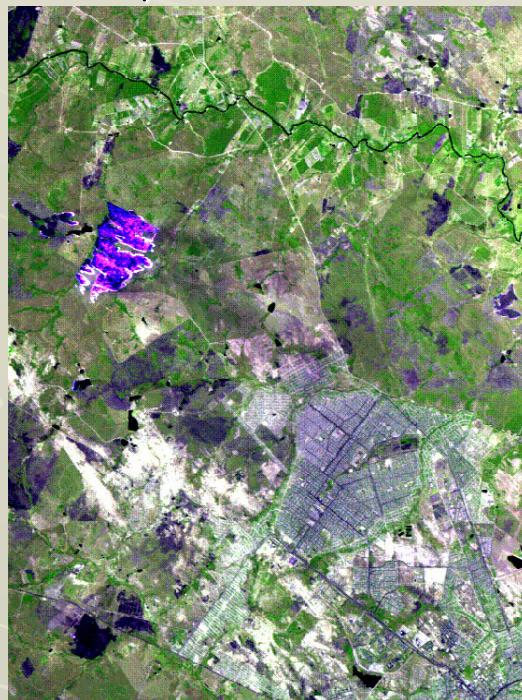
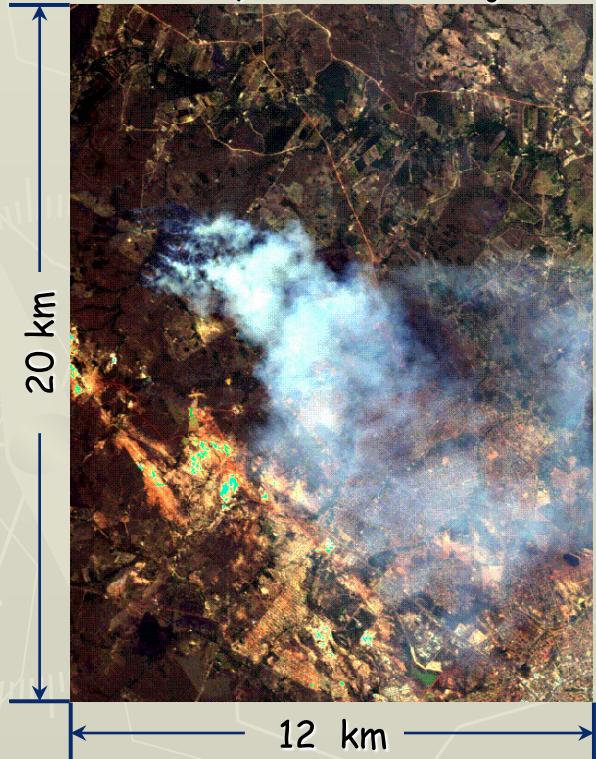
Aerosol Effects on Reflected Solar Radiation over Land

Biomass burning
Cuiabá, Brazil (August 25, 1995)

$$\begin{aligned} R &= 0.66 \mu\text{m} \\ G &= 0.55 \mu\text{m} \\ B &= 0.47 \mu\text{m} \end{aligned}$$

$$\begin{aligned} R &= 1.6 \mu\text{m} \\ G &= 1.2 \mu\text{m} \\ B &= 2.1 \mu\text{m} \\ \theta_0 &= 36^\circ \end{aligned}$$

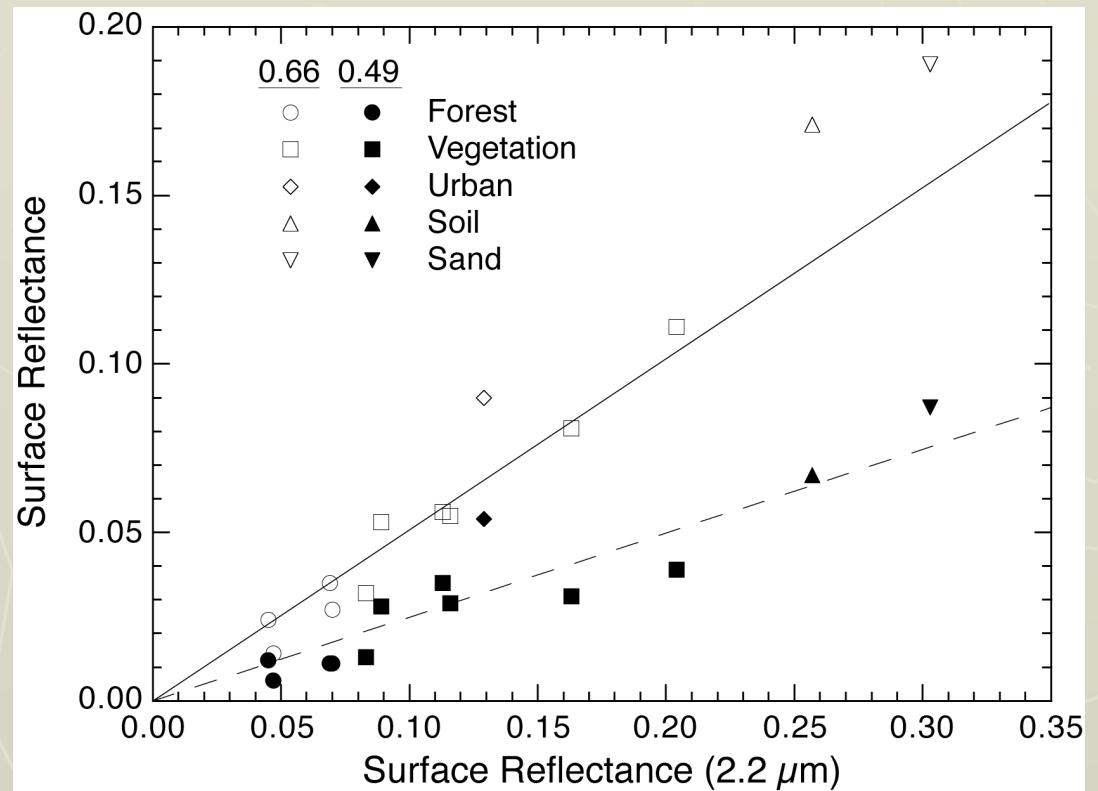
- [Green square] $A_g(2.1 \mu\text{m}) < 0.10$
- [Yellow square] $0.10 < A_g(2.1 \mu\text{m}) < 0.15$



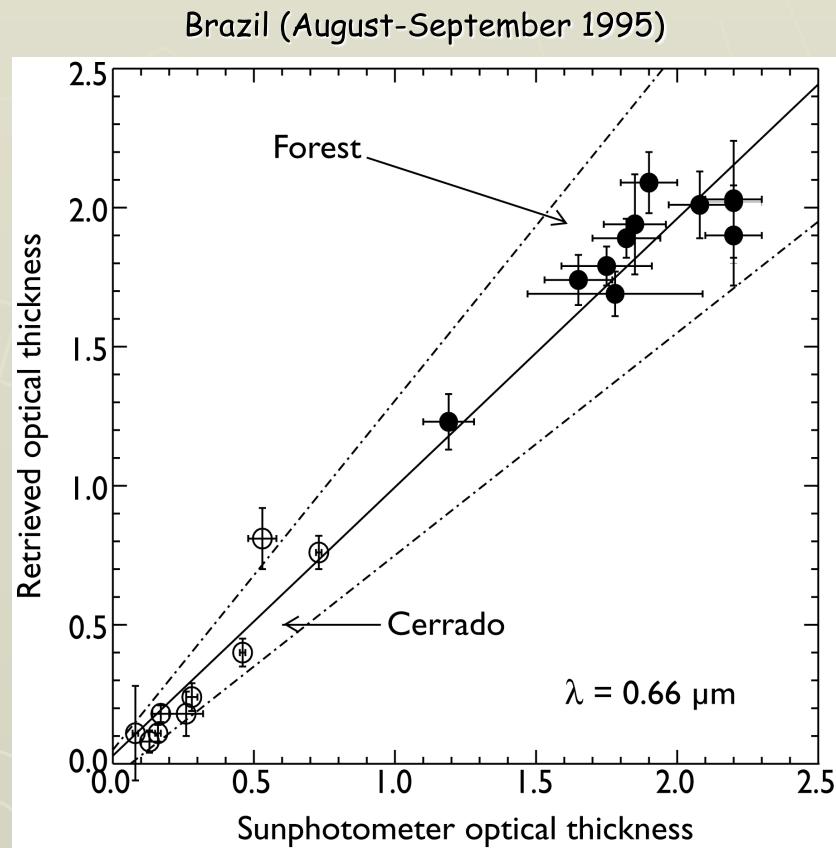
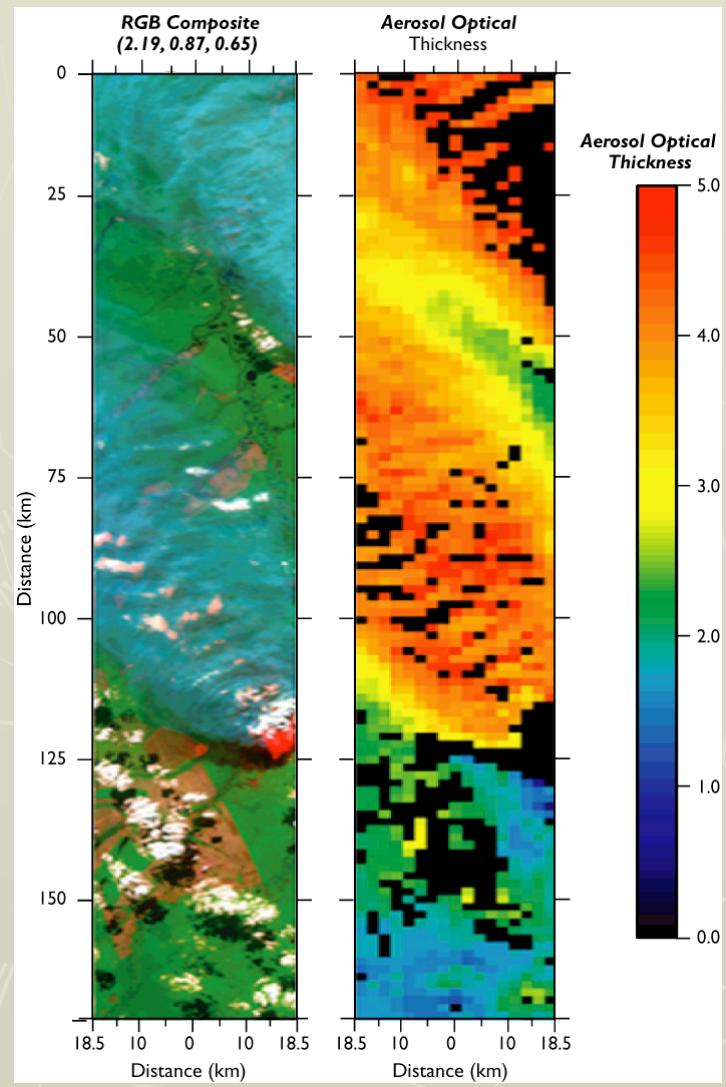
Surface Reflectance at Near-Infrared Wavelengths

(Y. J. Kaufman, A. Wald, L. A. Remer et al. - NASA GSFC, U. Lille)

- Surface reflectance is high at $2.2 \mu\text{m}$, moderate at $0.66 \mu\text{m}$, and low at $0.49 \mu\text{m}$
- The aerosol effect on reflected solar radiation is small at $2.2 \mu\text{m}$ and large at $0.49 \mu\text{m}$
- MODIS operational algorithm over land assumes
$$A_g(0.47 \mu\text{m}) = 0.5A_g(0.66 \mu\text{m}) \\ = 0.25A_g(2.1 \mu\text{m})$$



Remote Sensing of Aerosol over Land: SCAR-B (Brazil)



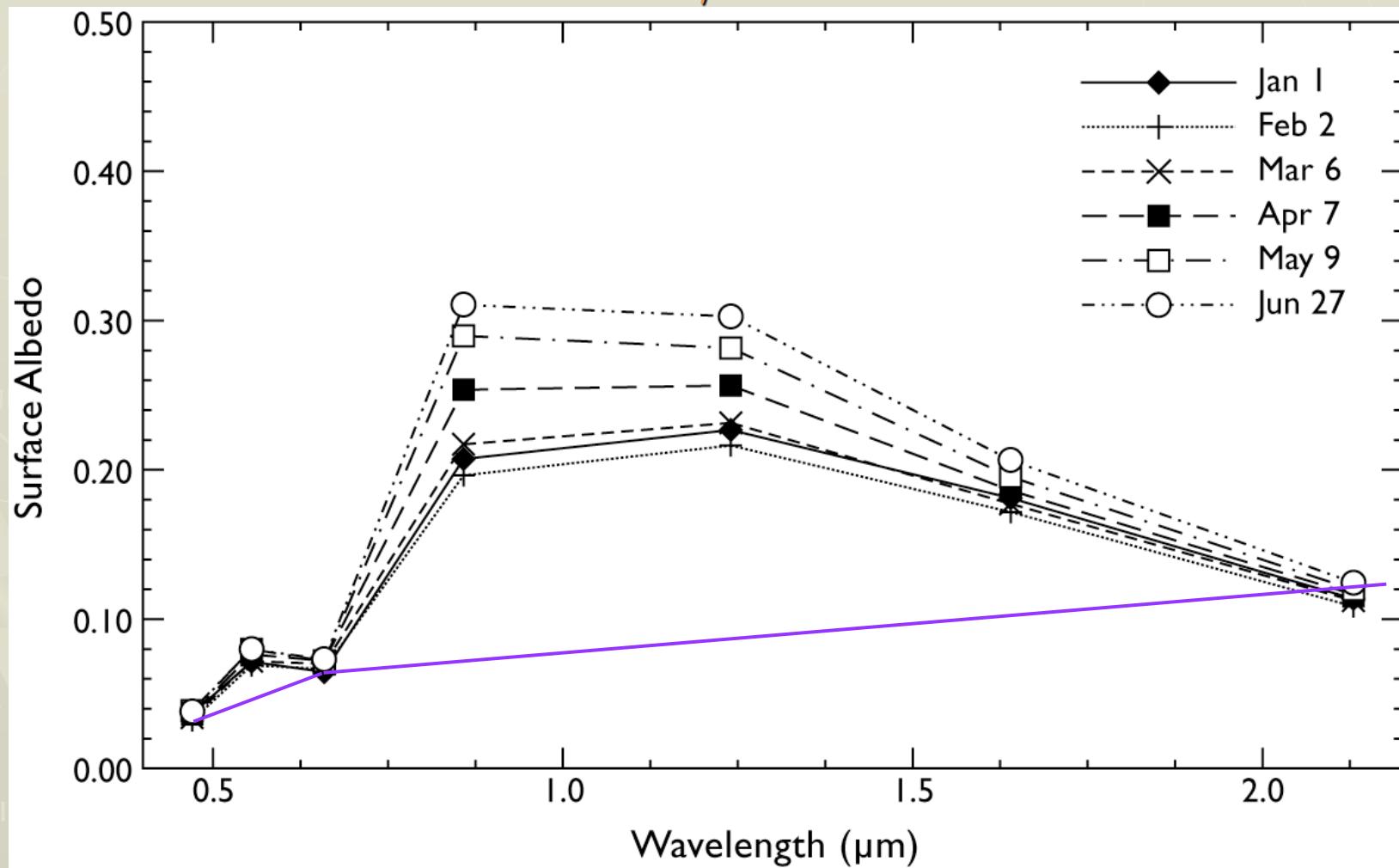
- Spectral optical thickness derived from MAS
- Intercomparison with ground-based AERONET
- Dotted lines are the retrieval error ($\Delta\tau_a = 0.05 \pm 0.2\tau_a$) anticipated using the MODIS aerosol optical thickness retrieval algorithm

Chu et al. (1998)

Spectral Variability of Urban Ecosystem

(E. G. Moody, M. D. King, C. B. Schaaf, S. Platnick - GSFC, Boston U.)

January - June



Aerosol Optical Thickness & Fine Mode Fraction

(L. A. Remer, Y. J. Kaufman, D. Tanré - GSFC, Univ. Lille)

Aqua/MODIS

➤ Fine Mode

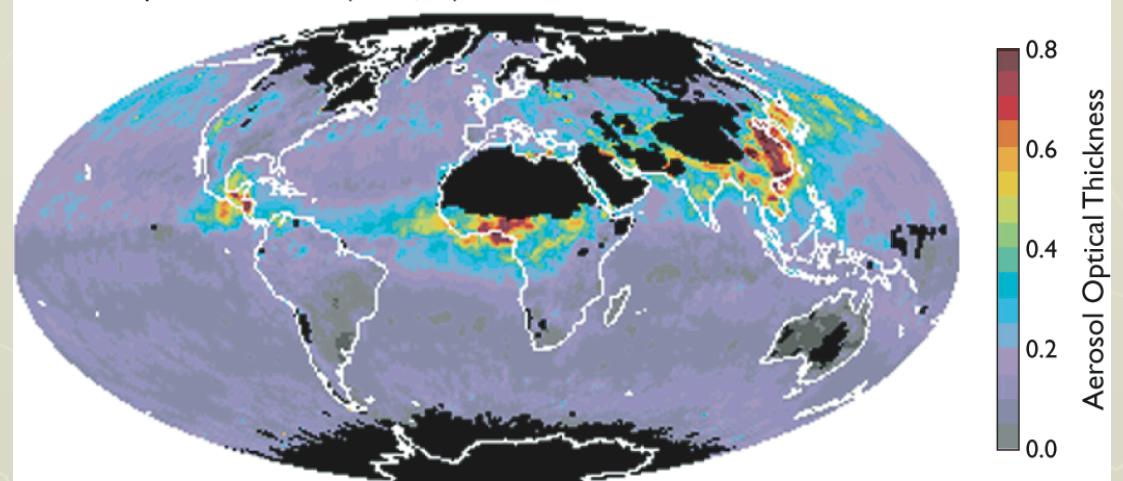
- Industrial pollution
 - ✓ China, India, US, Europe
- Smoke from biomass burning
 - ✓ Brazil and Bolivia
 - ✓ Southern Africa (DRC, Angola, Zambia)
 - ✓ Australia, Borneo

➤ Coarse Mode

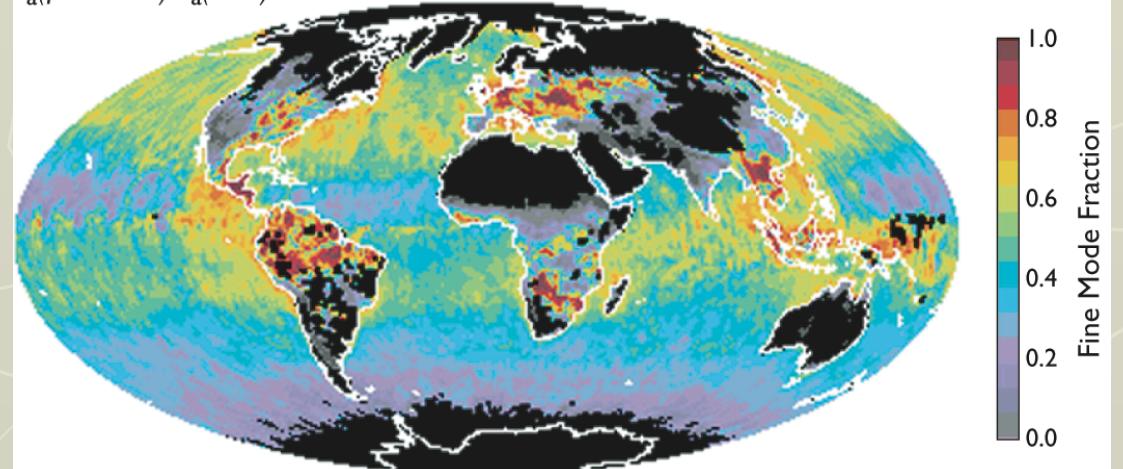
- Desert dust
 - ✓ Sahara, Arabian Sea
- Sea salt
 - ✓ Southern Ocean

April 2005

Aerosol Optical Thickness (0.56 μm)

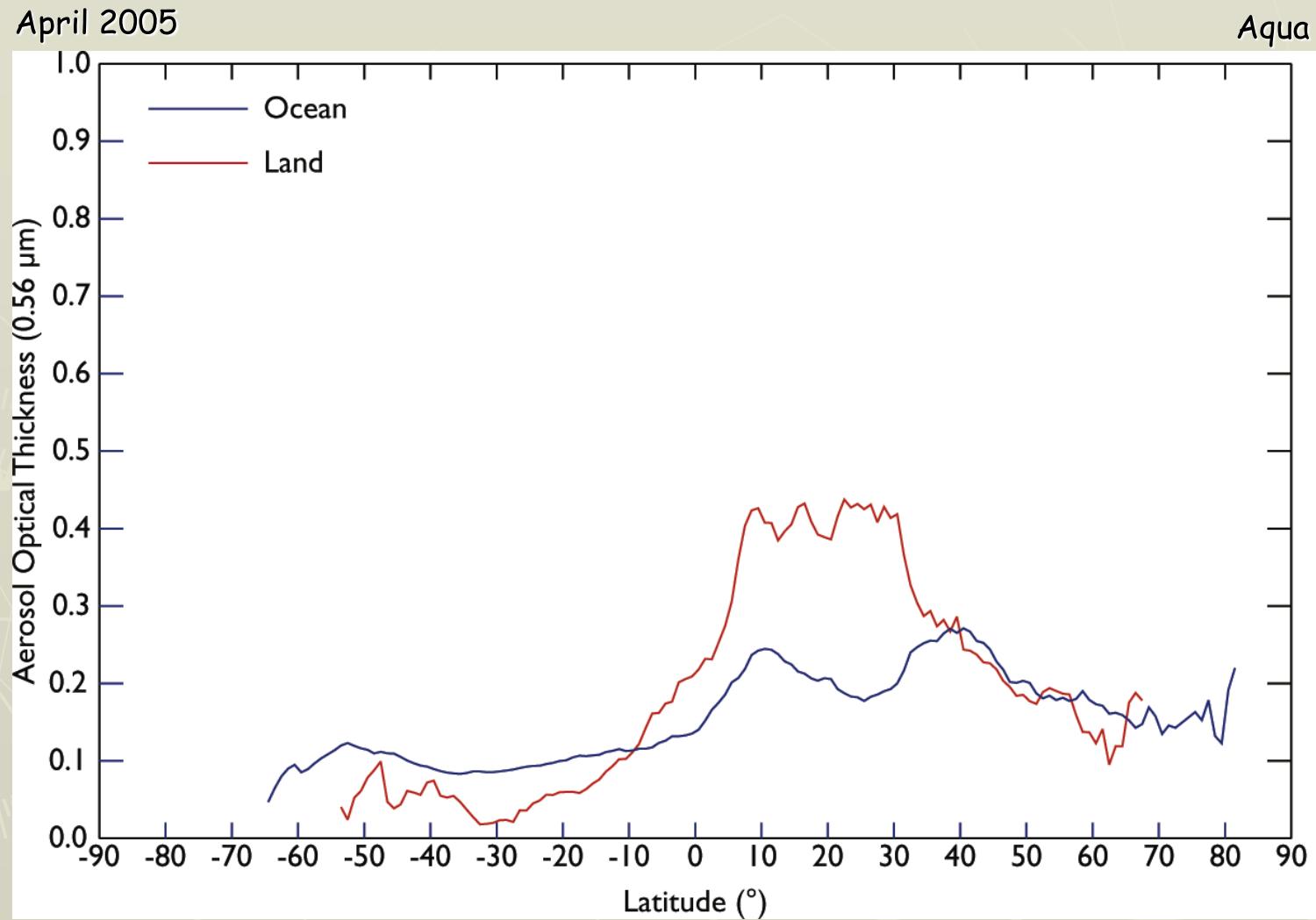


$\tau_a(\text{fine mode})/\tau_a(\text{total})$



Zonal Mean Aerosol Optical Thickness

(L. A. Remer, Y. J. Kaufman, and D. Tanré - NASA GSFC, U. Lille)

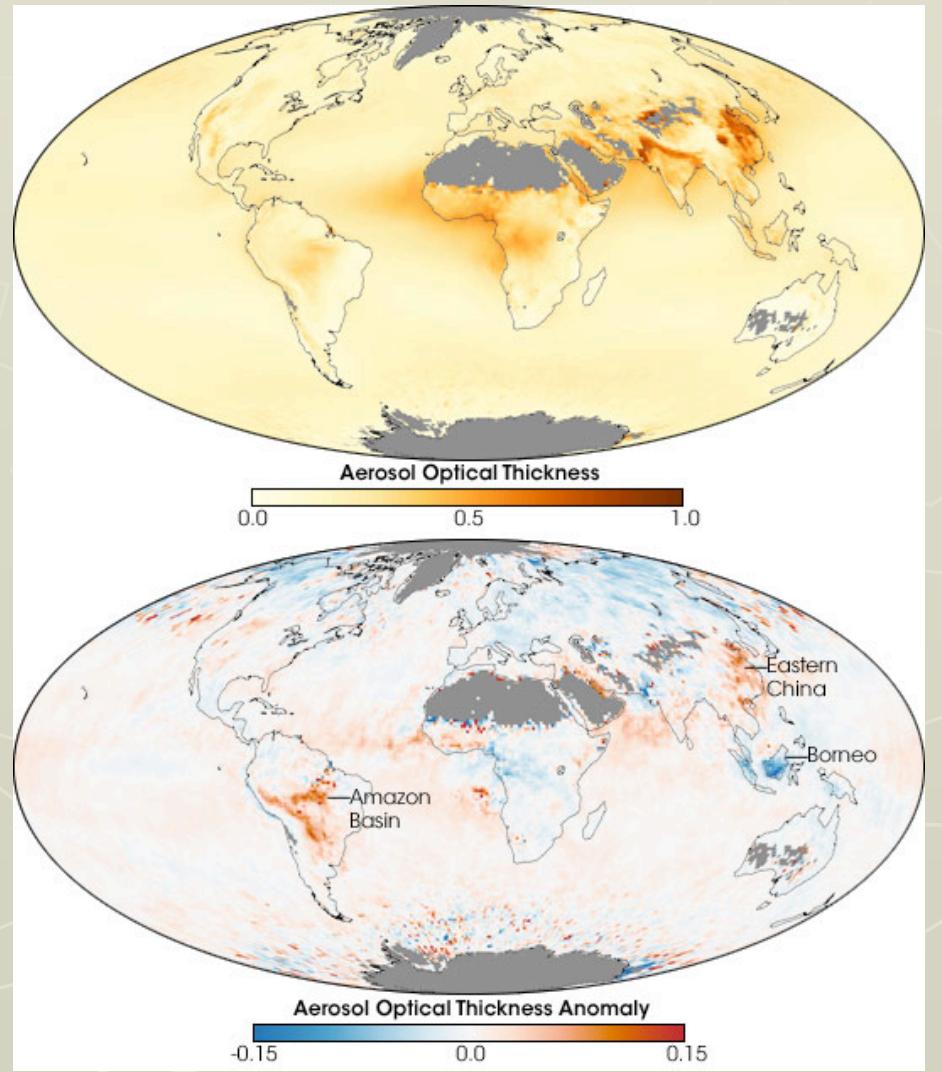


MODIS Aerosol Optical Thickness

(L. A. Remer, Y. J. Kaufman, D. Tanré - GSFC, Univ. Lille)

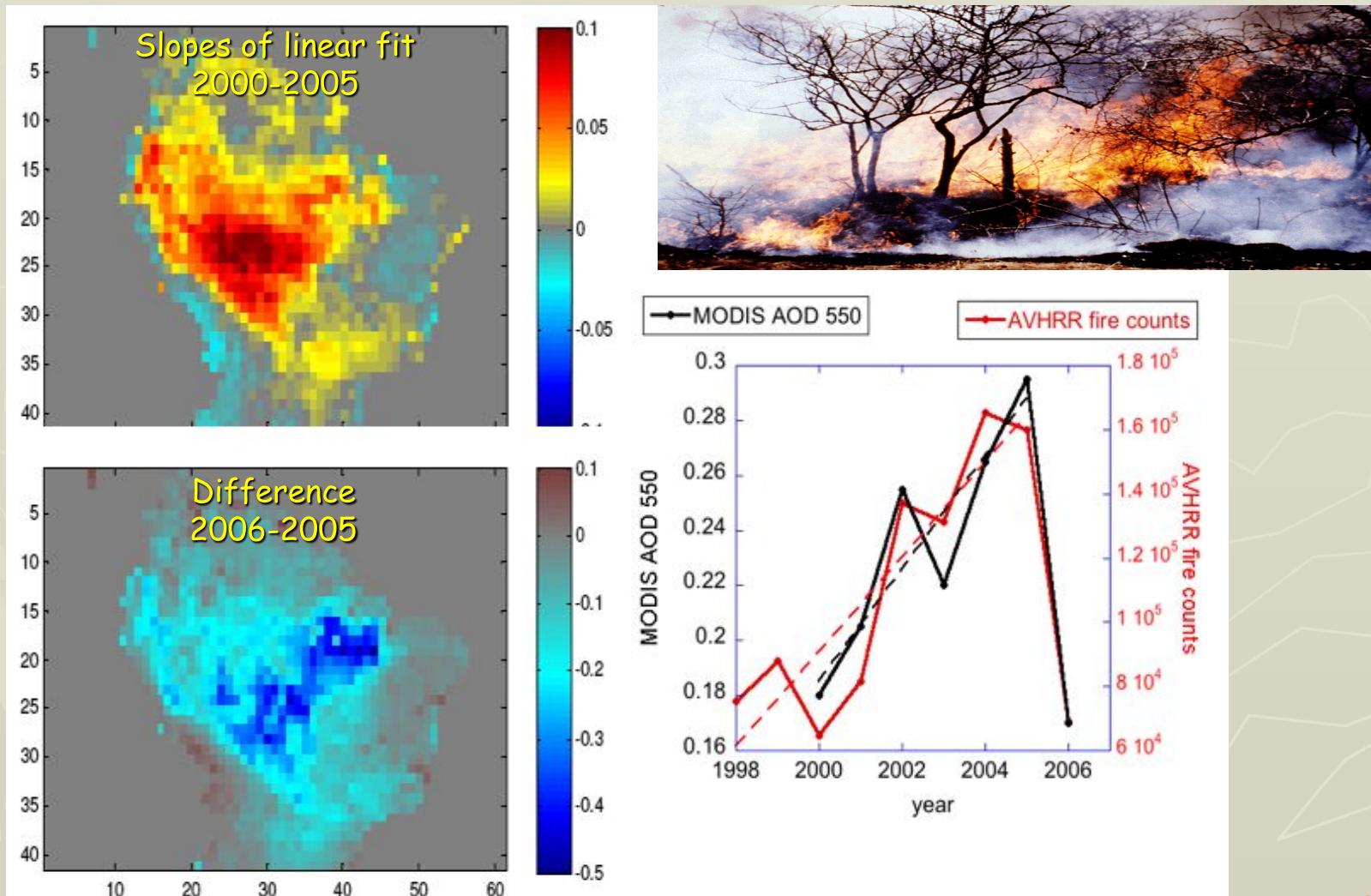
Terra/MODIS

- Climatology (2000-2007)
 - Industrial pollution
 - ✓ China, India
 - Smoke from biomass burning
 - ✓ Brazil and Bolivia
 - ✓ Africa (DRC, Sub-Sahel)
 - Dust
 - ✓ Sahara, Iraq, Arabian Sea
- Anomaly (2007)
 - Enhancement
 - ✓ Amazon basin
 - ✓ Eastern China
 - Reduction
 - ✓ Borneo
 - ✓ Eurasia, Alaska



Reversal in Trend of Biomass Burning in the Amazon

(I. Koren, L. A. Remer, K. Longo - Weizmann Inst., GSFC, INPE)

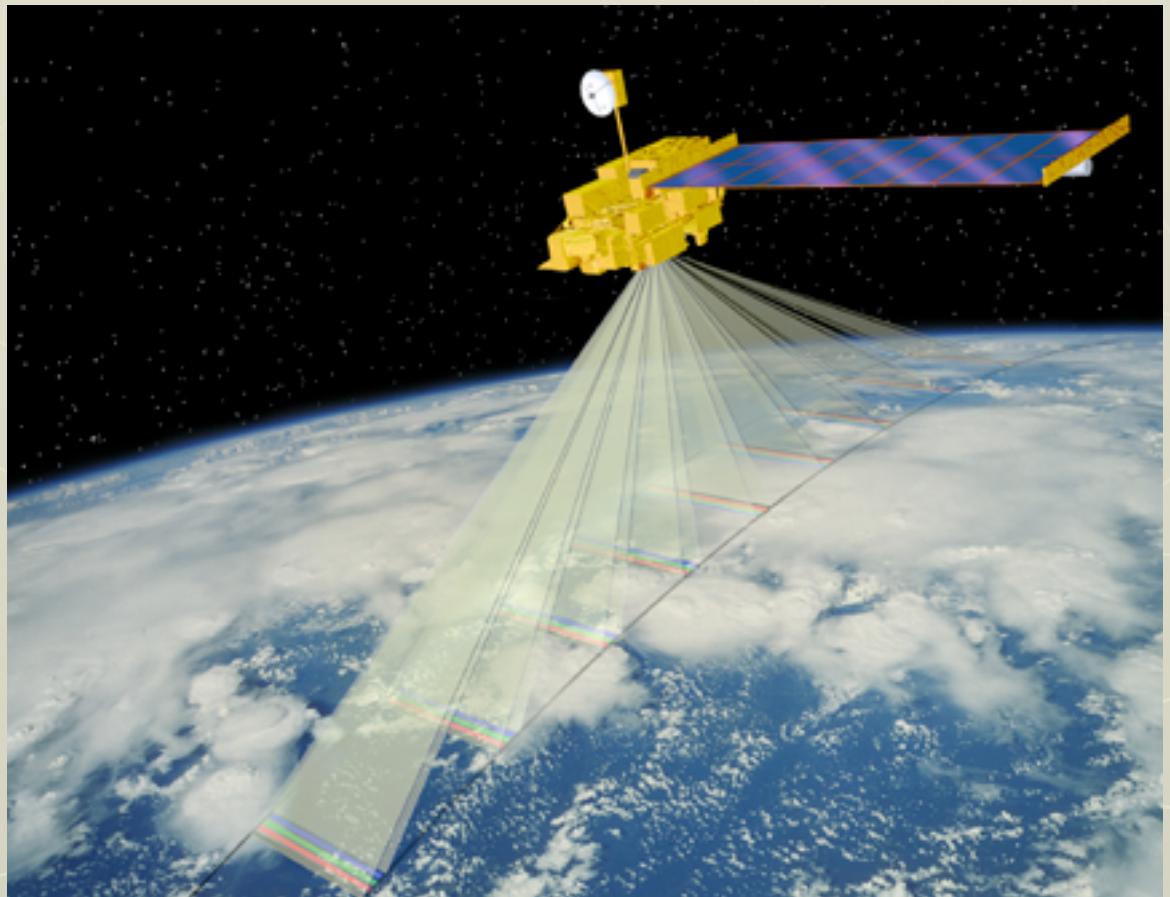
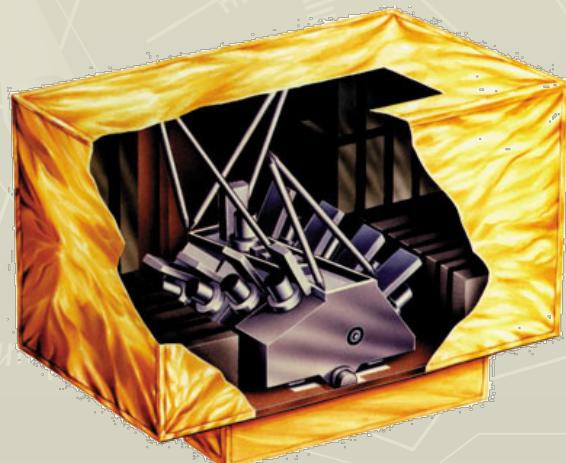


Koren et al. (2007)

Multi-angle Imaging SpectroRadiometer (MISR)

Terra/MISR

- MISR sees the Earth at 9 look angles, which enable stereoscopic images; unprecedented for studies of land surface cover, cloud & aerosol structures, & angular reflectance



- Nine pushbroom cameras
- Nine view angles at Earth surface: 70.5° forward to 70.5° aft
- Four spectral bands at each angle: 446, 558 672, 866 nm

MISR Provides New Angle on Haze

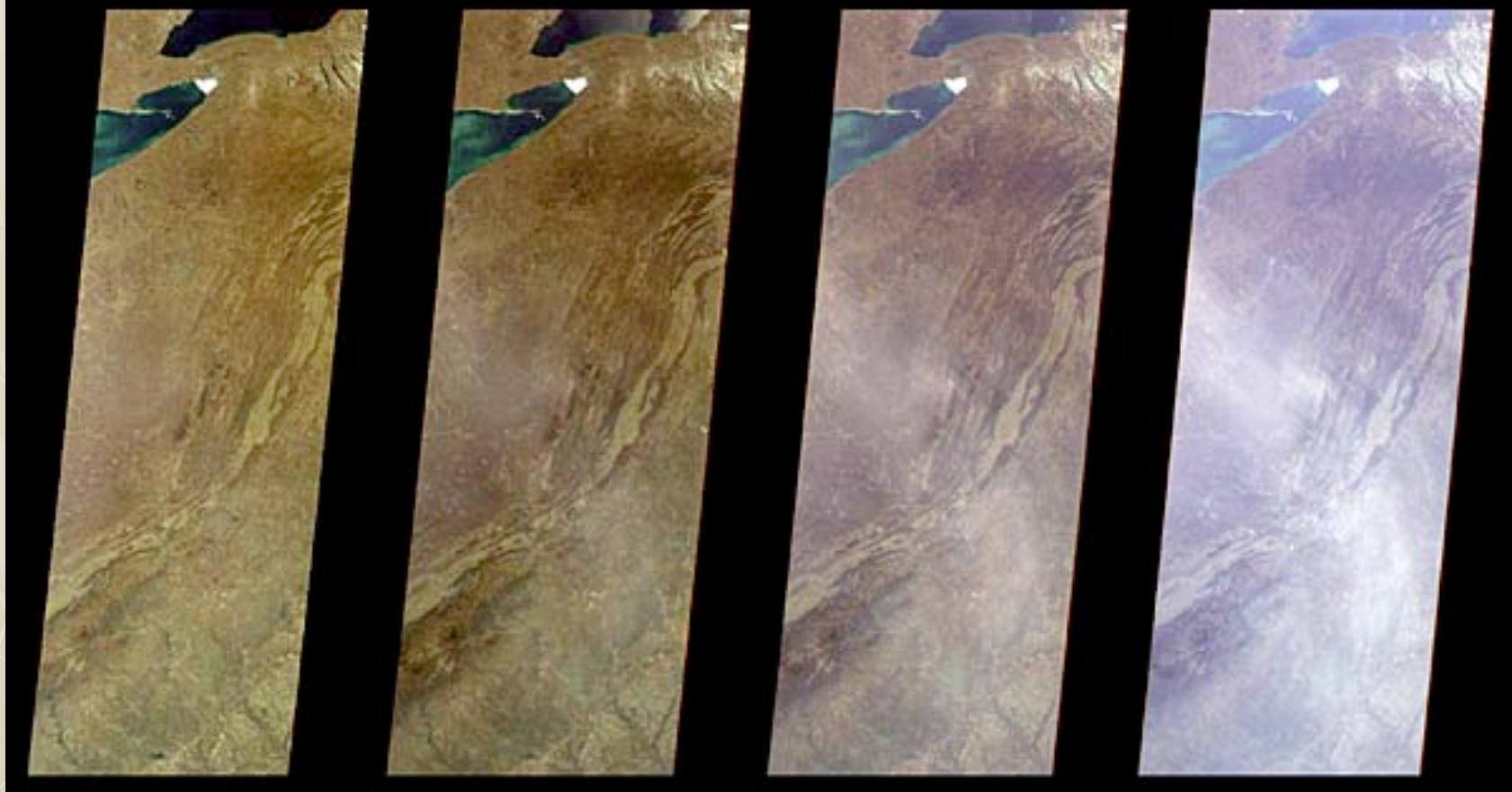
June 14, 2000

0°

45.6° forward

60° forward

70.5° forward

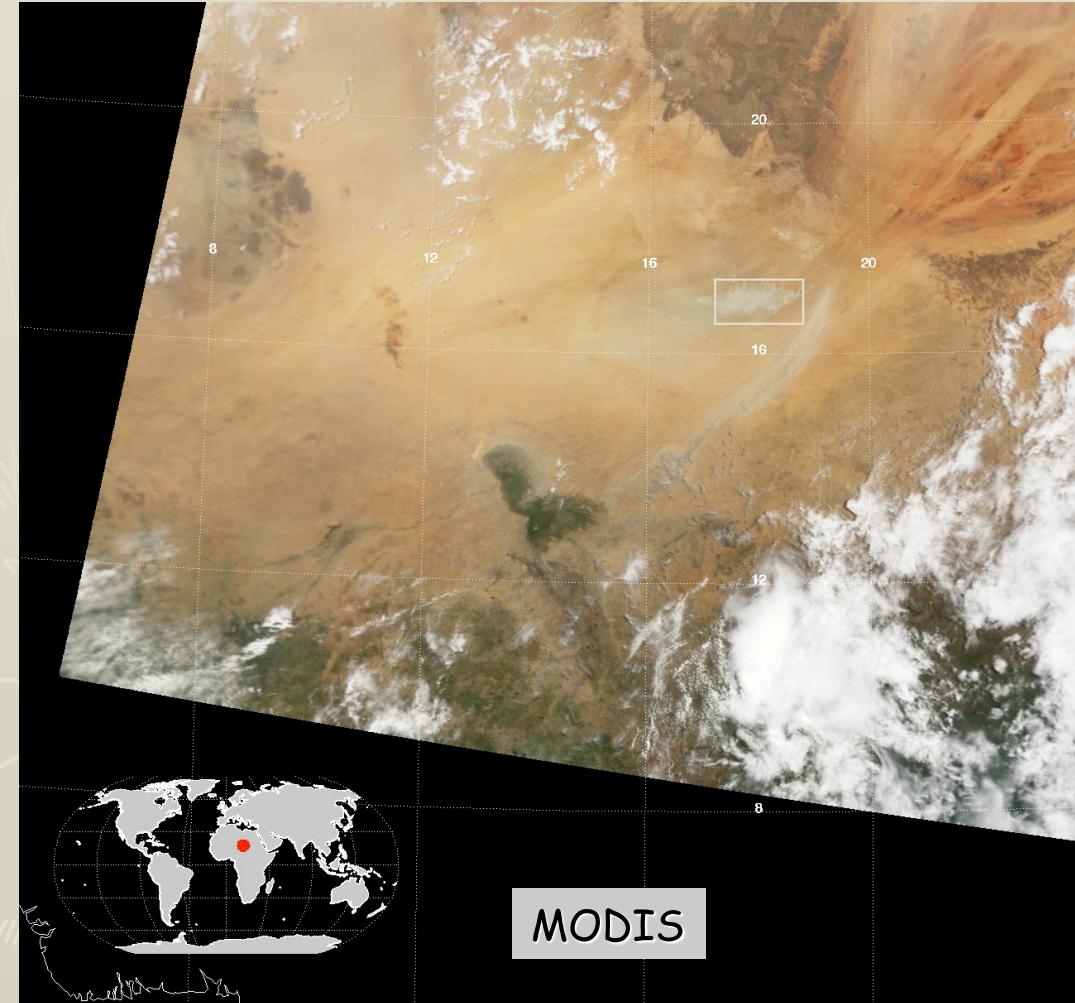


- In this MISR view spanning from Lake Ontario to Georgia, the increasingly oblique view angles reveal a pall of haze over the Appalachian Mountains

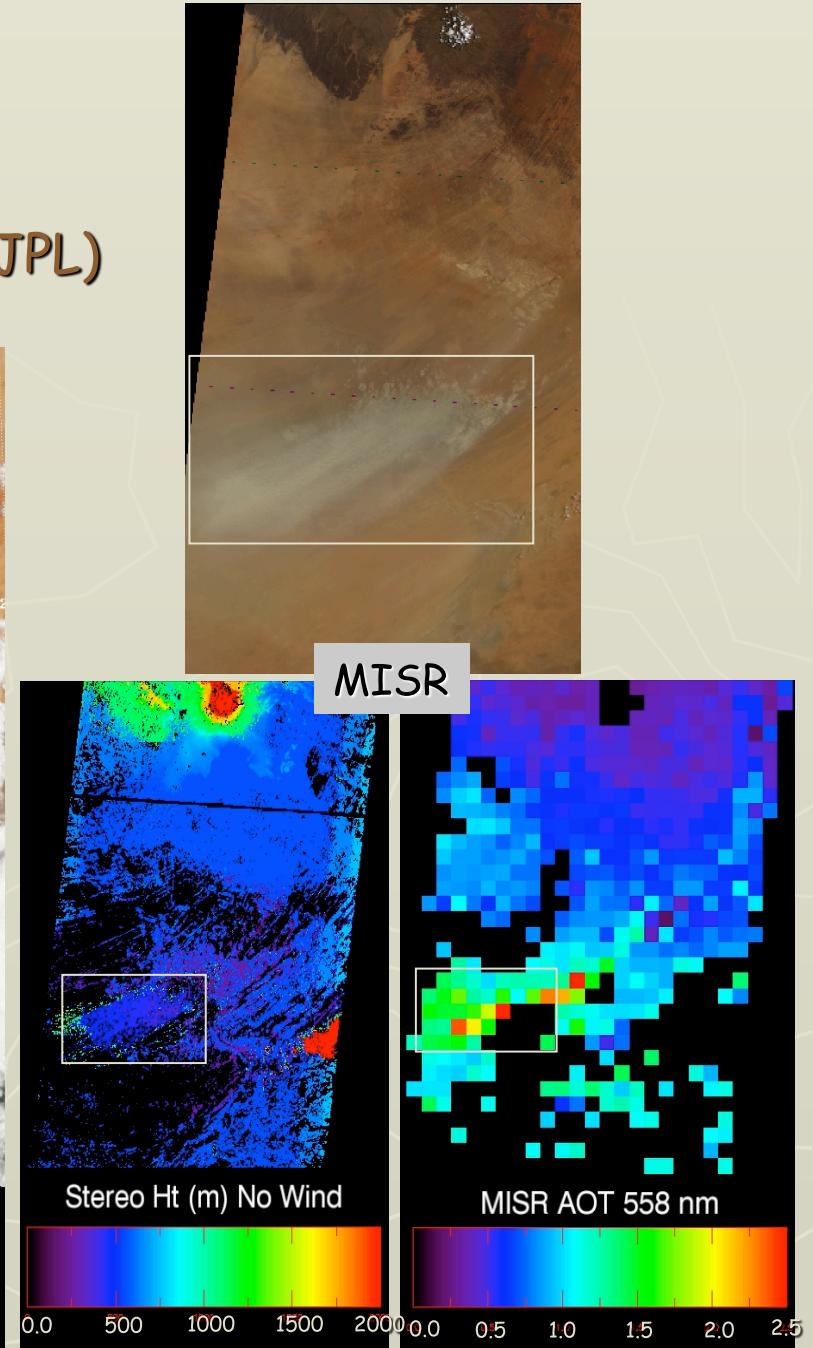
Saharan Dust Source Plume

(R. A. Kahn, W. H. Li, C. Moroney et al. - JPL)

June 3, 2005



Dust is injected near-surface...

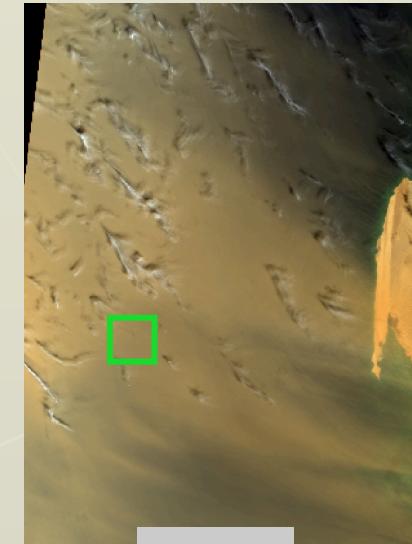
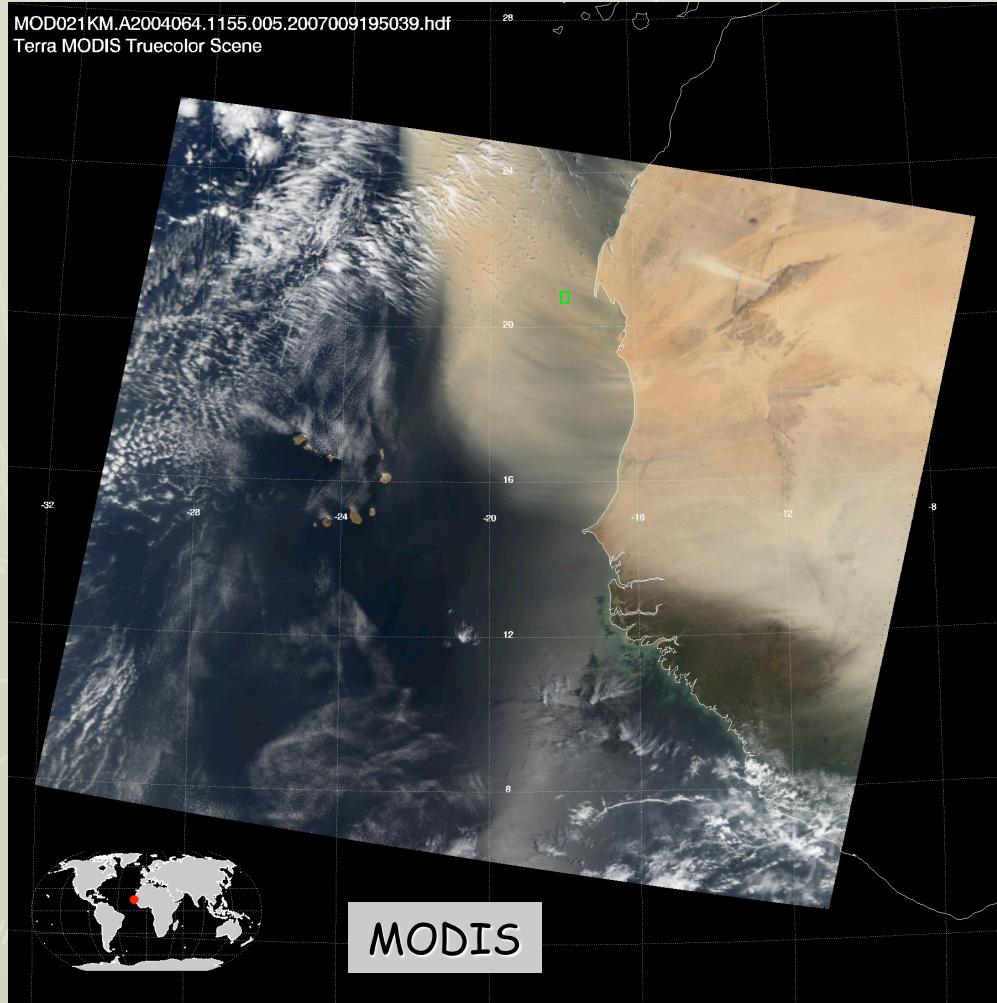


Kahn et al. (2007)

Transported Dust Plume

(R. A. Kahn, W. H. Li, C. Moroney et al. - JPL)

March 4, 2004



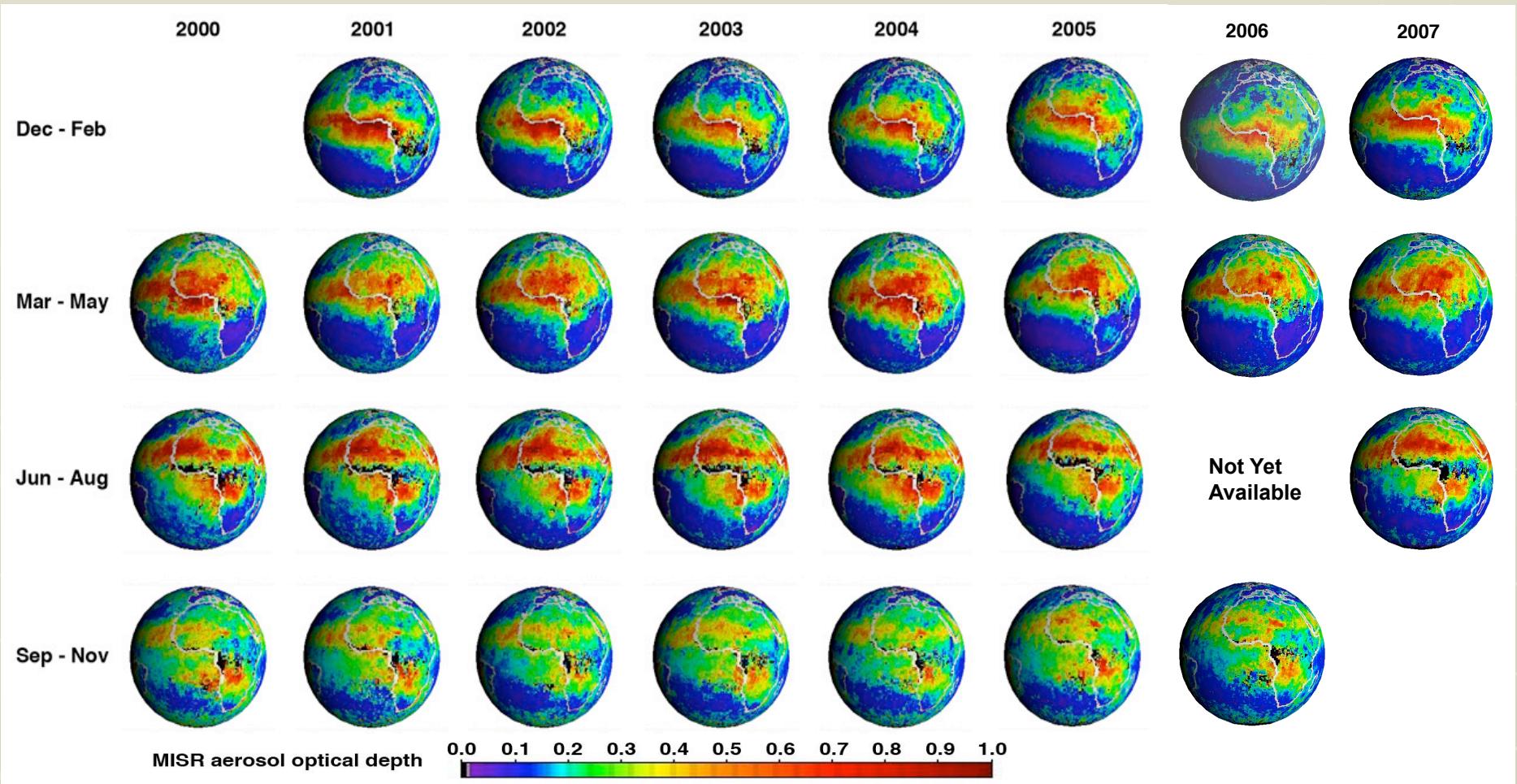
MISR

Transported dust finds elevated layer of relative stability...

Kahn et al. (2007)

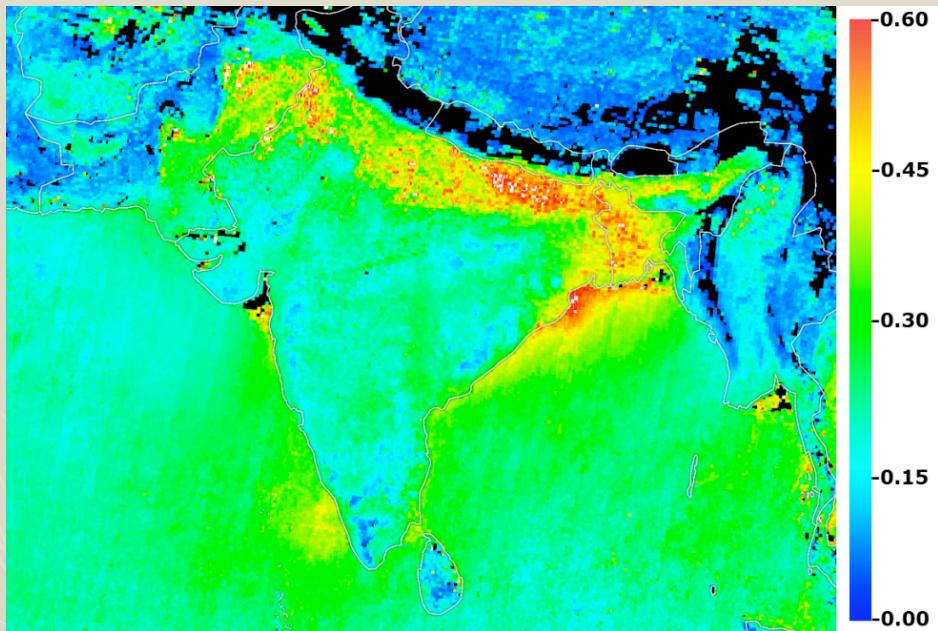
MISR Aerosol Optical Thickness

(D. J. Diner, R. A. Kahn et al. - JPL, GSFC)

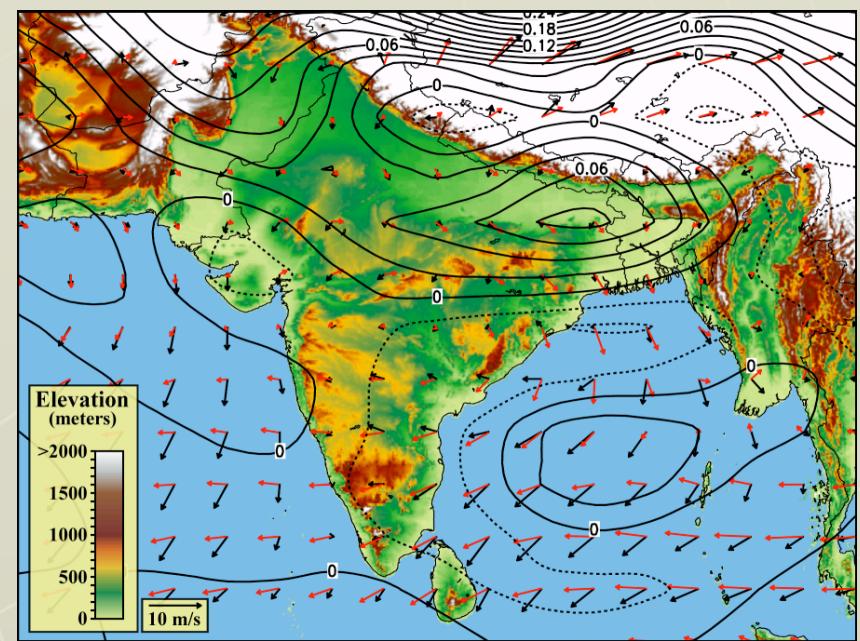


MISR Aerosol Concentration in Indo-Gangetic Plain

(L. DiGirolamo, T. C. Bond, D. Bramer et al. - U. Illinois, JPL)



MISR mid-visible Aerosol Optical Thickness
[Winter, 2001-2004; white \rightarrow AOD > 0.6]

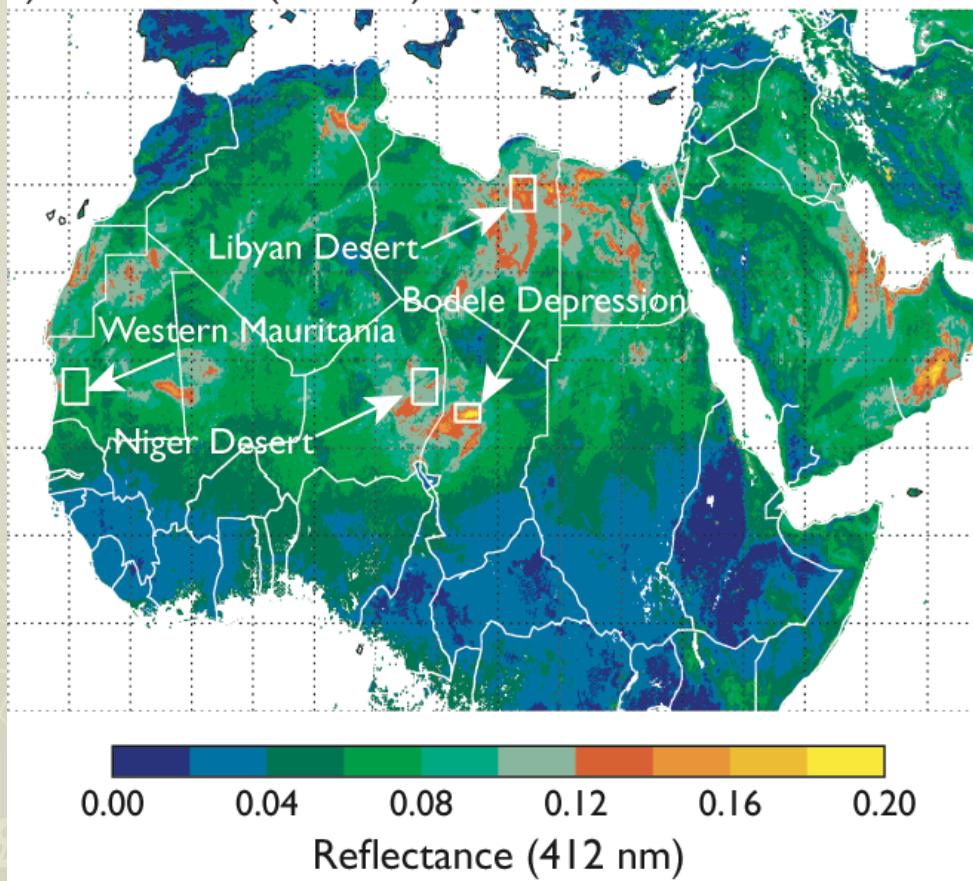


NCEP Winds + Topography
[Black = surface; Red = 850 hPa;
contours = vertical, solid = subsidence]

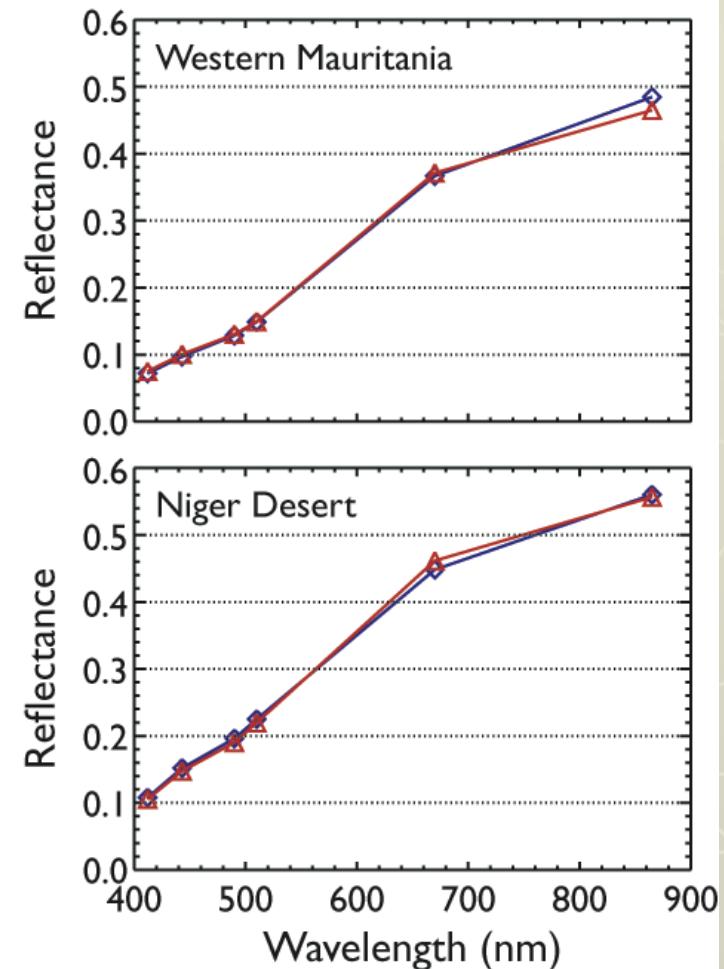
Spectral Surface Albedo of Saharan Desert

(N. C. Hsu, S. C. Tsay, M. D. King, and J. R. Herman - NASA GSFC)

a) Reflectance (412 nm)



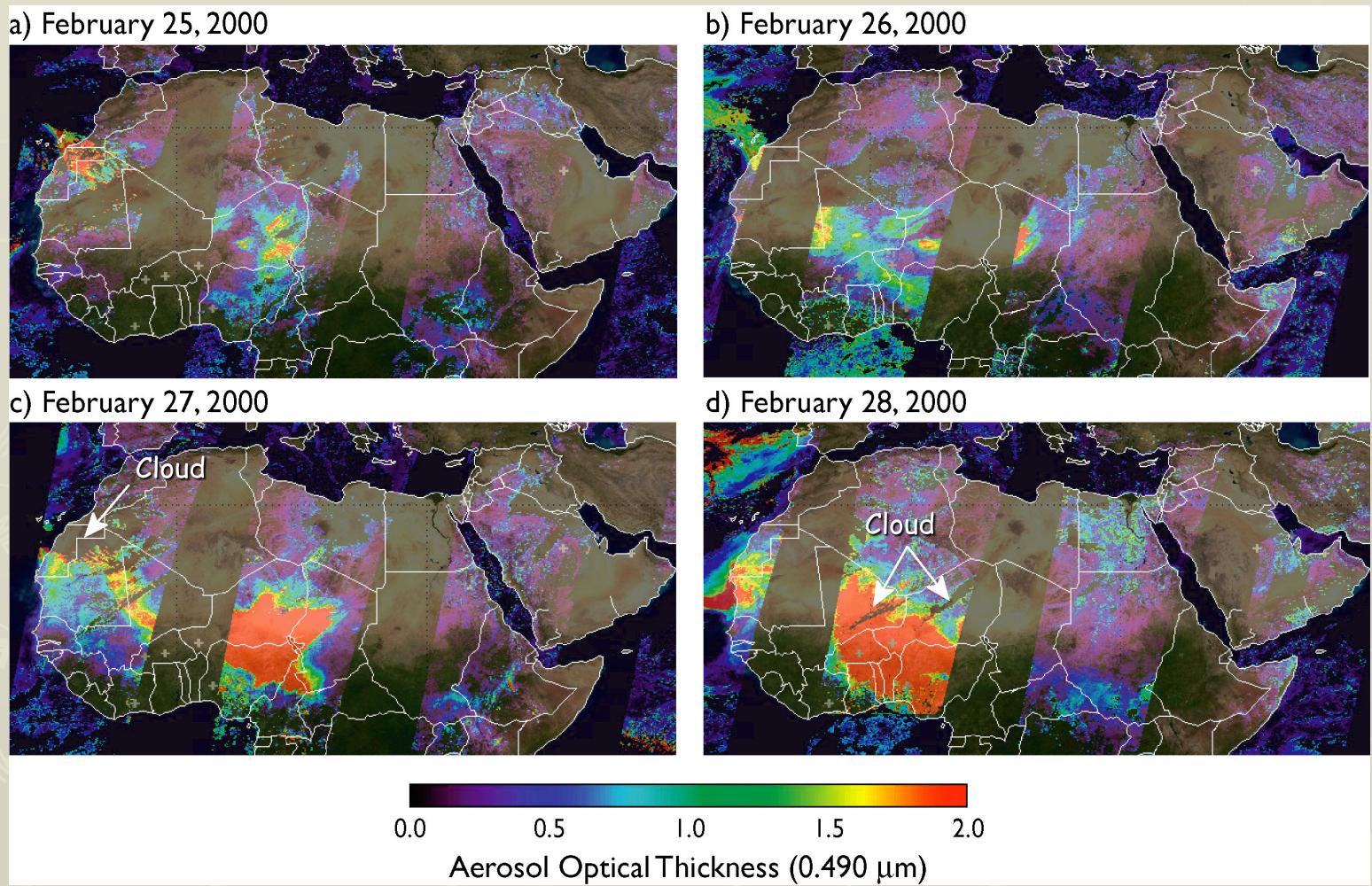
c) Spectral Reflectance



Aerosol Optical Thickness of Dust in Africa

Deep Blue Algorithm

SeaWiFS

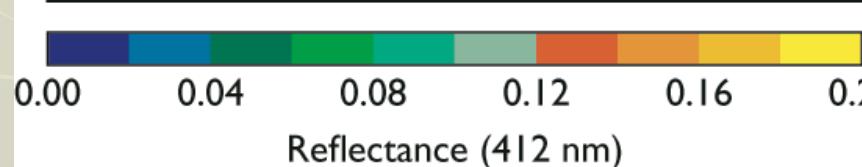
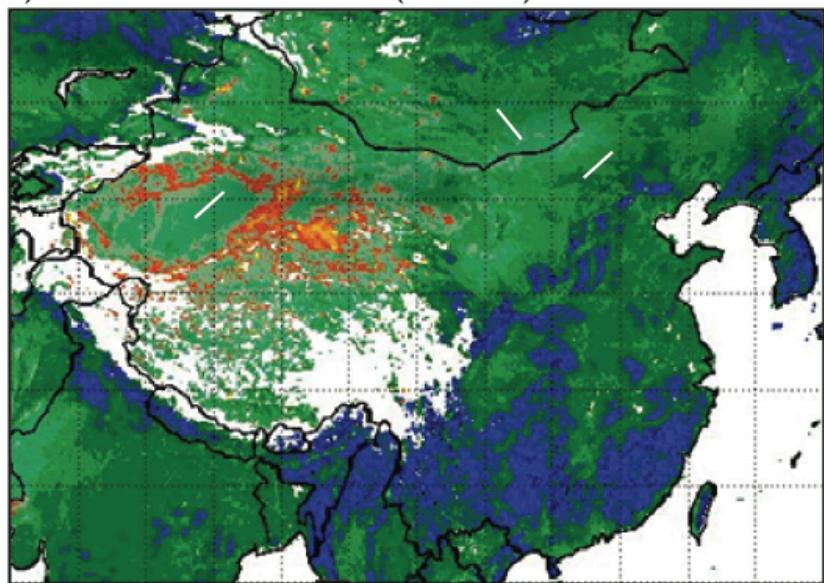


Hsu et al. (2004)

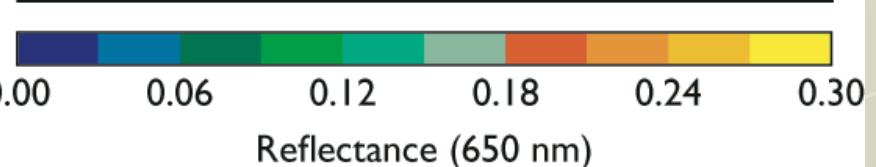
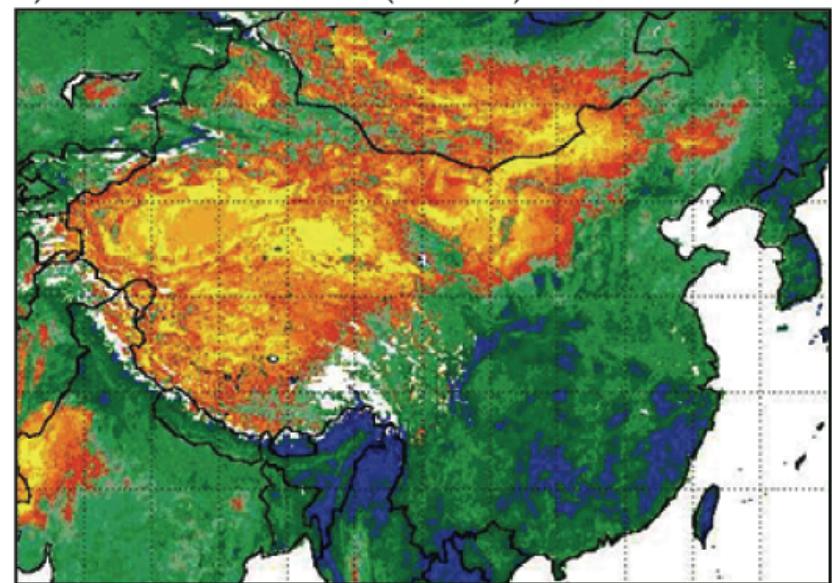
Spectral Surface Albedo of China

(N. C. Hsu, S. C. Tsay, M. D. King, and J. R. Herman - NASA GSFC)

a) SeaWiFS Reflectance (412 nm)



b) MODIS Reflectance (650 nm)

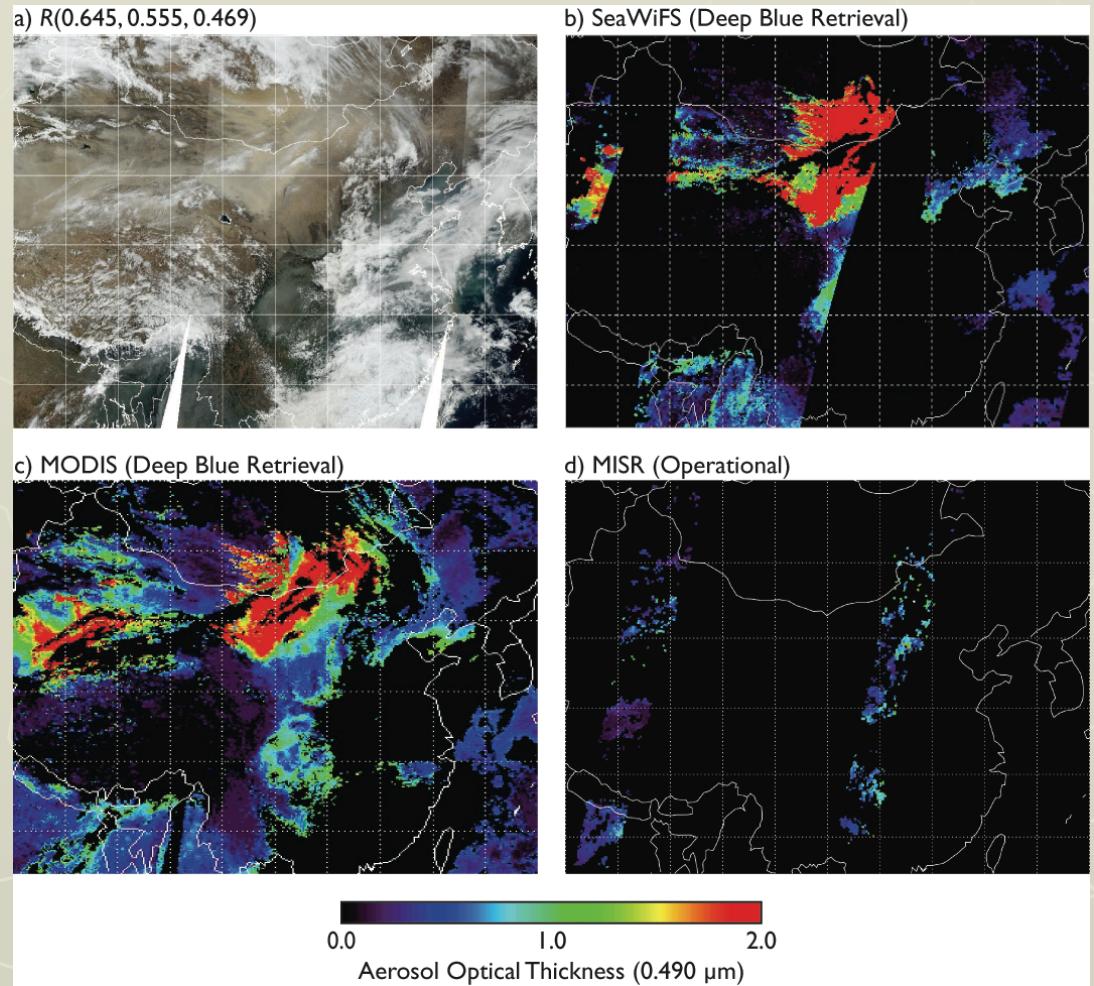


Aerosol Optical Thickness of Dust in Asia

(N. C. Hsu, S. C. Tsay, M. D. King, and J. R. Herman - NASA GSFC)

Deep Blue Algorithm

- Deep Blue retrieval of τ_a for SeaWiFS is similar to MODIS
 - MODIS has somewhat wider swath width
- MISR retrieval accurate over bright surfaces
 - Swath width is narrow (360 km)
 - Daily retrievals are impacted by swath width and clouds
 - Extreme events often missed

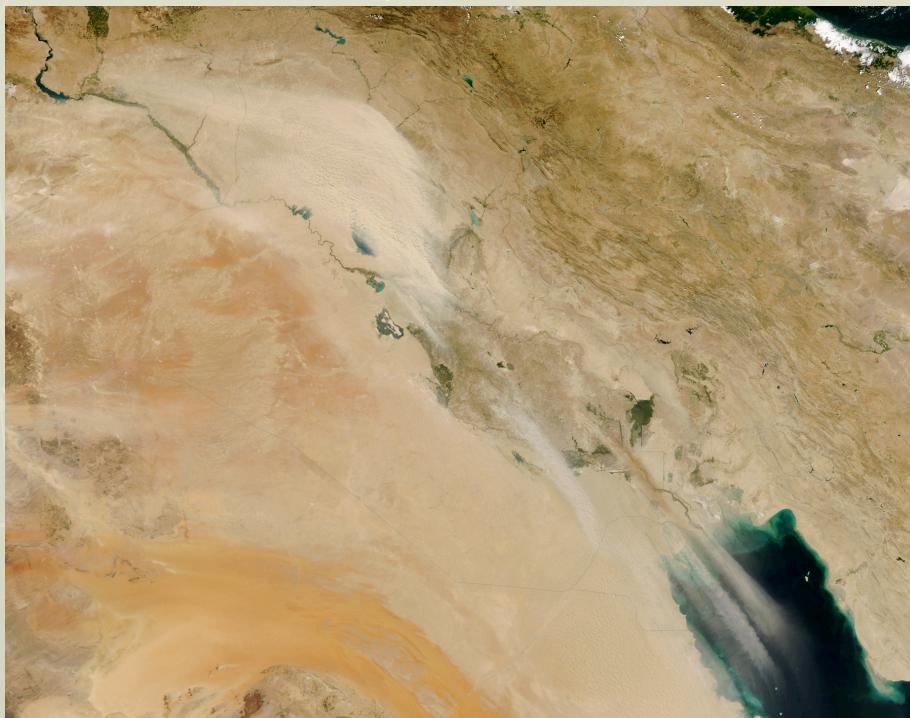


MODIS Deep Blue Algorithm over the Middle East

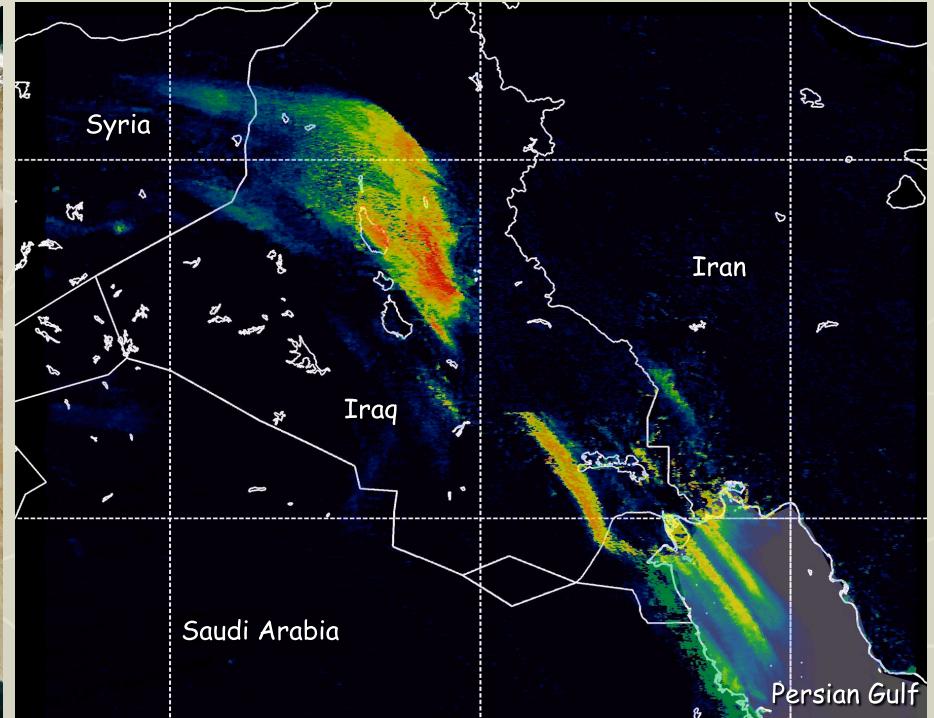
(N. C. Hsu , S. C. Tsay, M. D. King, and D. J. Diner - GSFC, JPL)

August 7, 2005

True Color Composite (0.65, 0.56, 0.47)



Aerosol Optical Thickness



0.0 0.5 1.0 1.5 2.0 2.5

Aerosol Optical Thickness

Shamal Dust Front over Al Asad Air Base Iraq

April 26, 2005

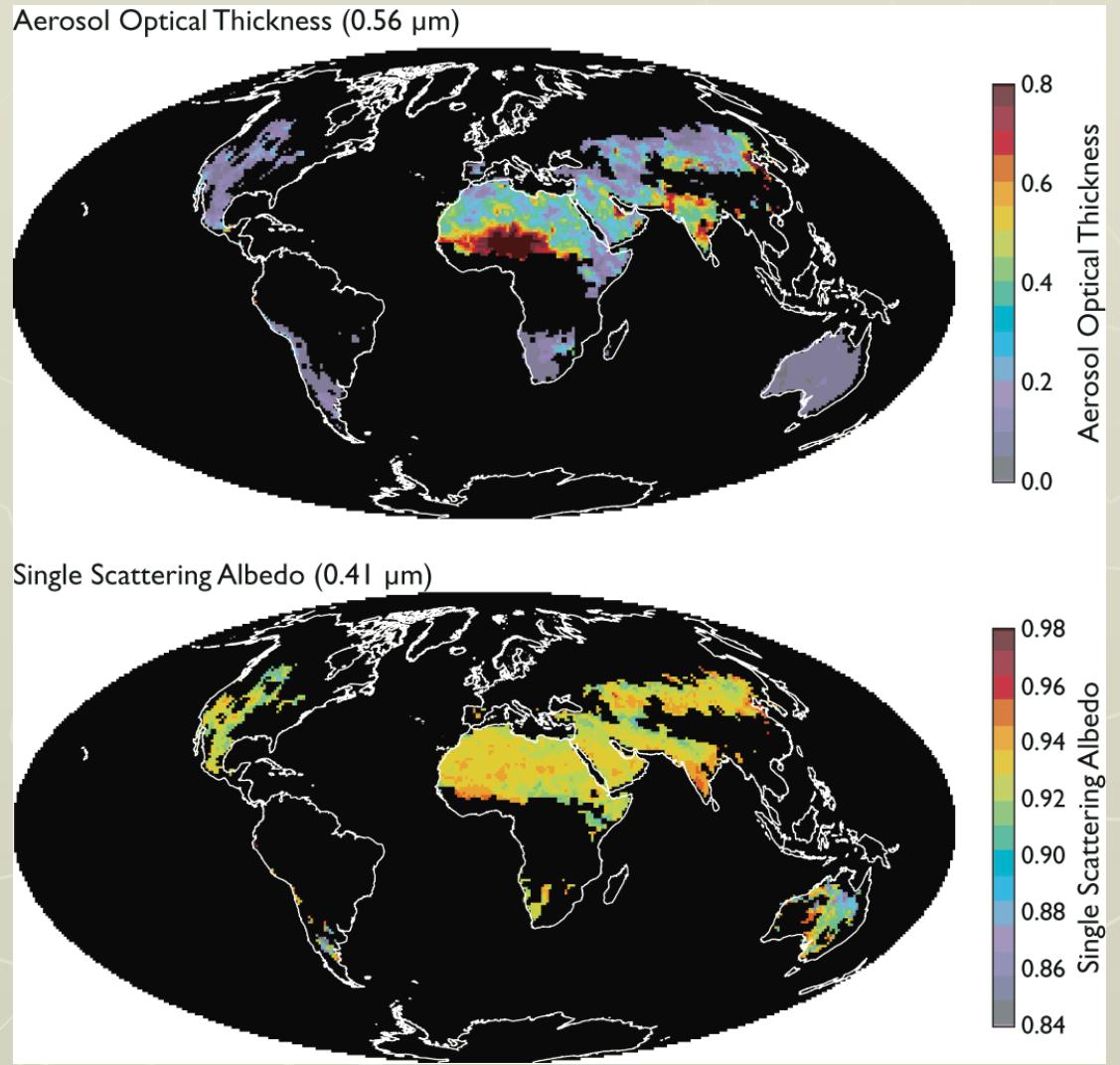


Aerosol Optical Thickness & Single Scattering Albedo

(N. C. Hsu, S. C. Tsay, M. D. King, and J. R. Herman - GSFC)

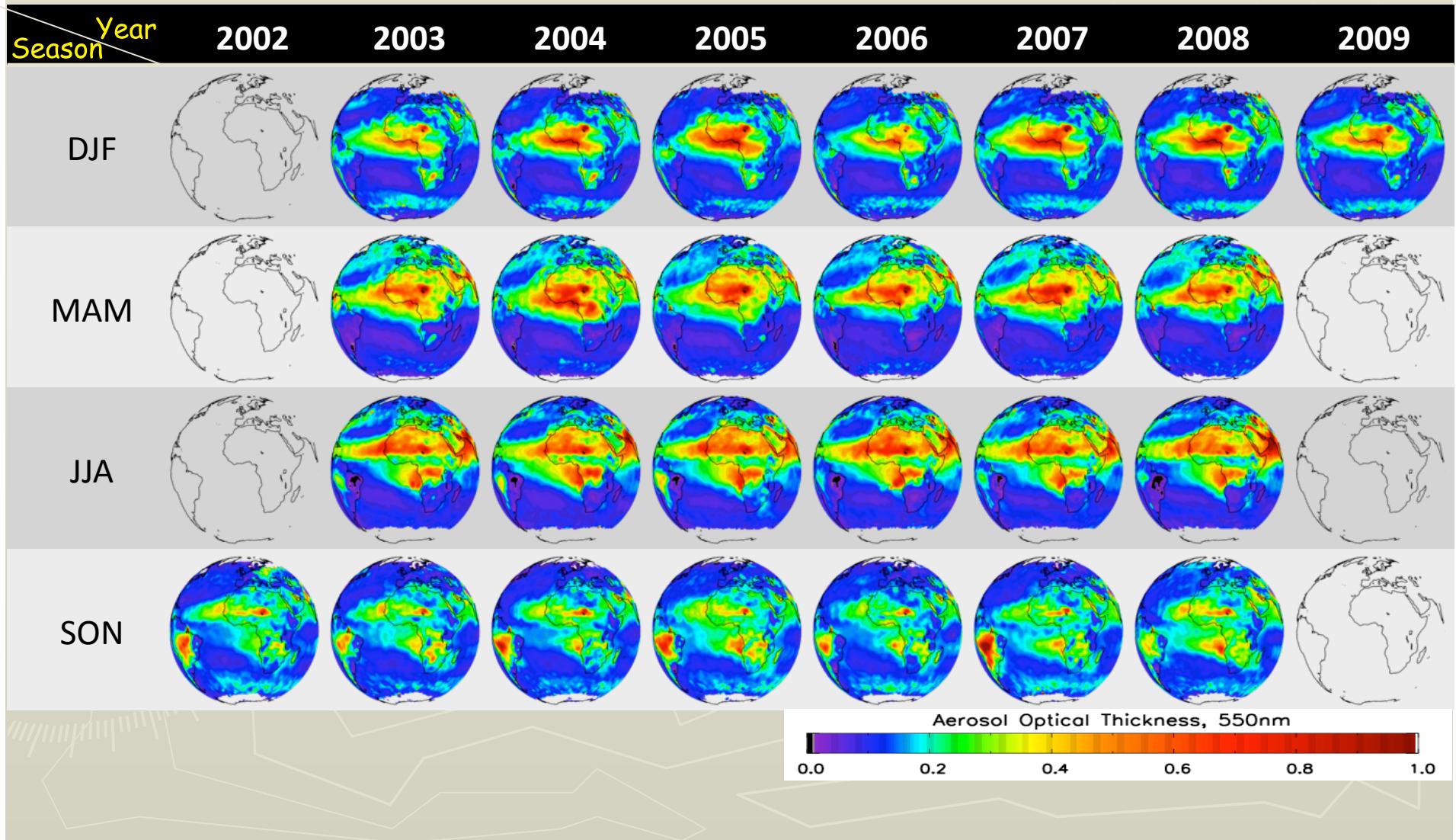
Aqua/MODIS

- Aerosol optical thickness
 - Dust over bright surfaces
 - ✓ Sahara desert
 - ✓ India
 - ✓ China and southwestern Asia
- Single scattering albedo
 - Desert dust
 - ✓ Gobi desert more absorbing than Taklimakan
 - ✓ Northern India more absorbing than southern India

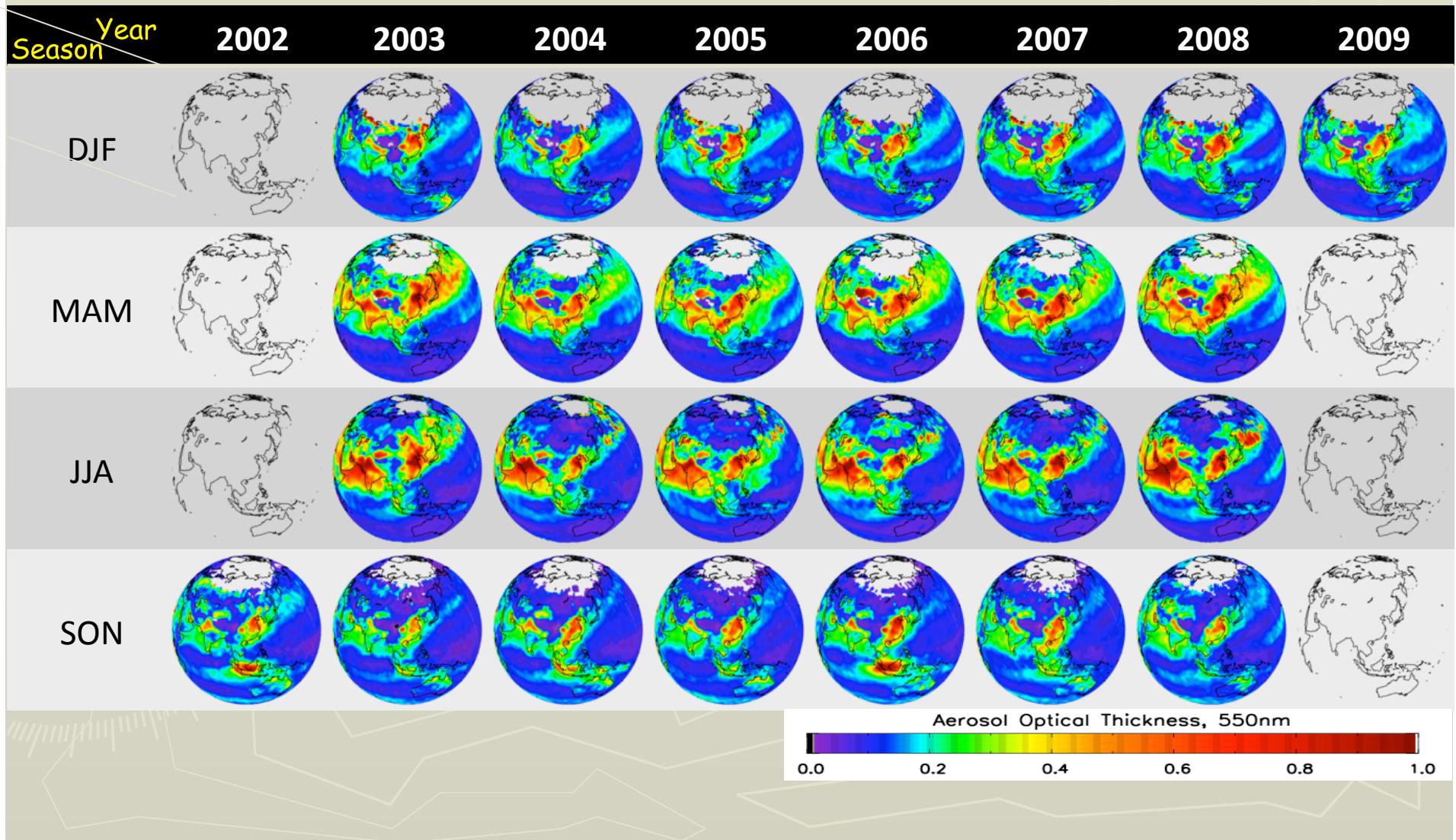


April 2005

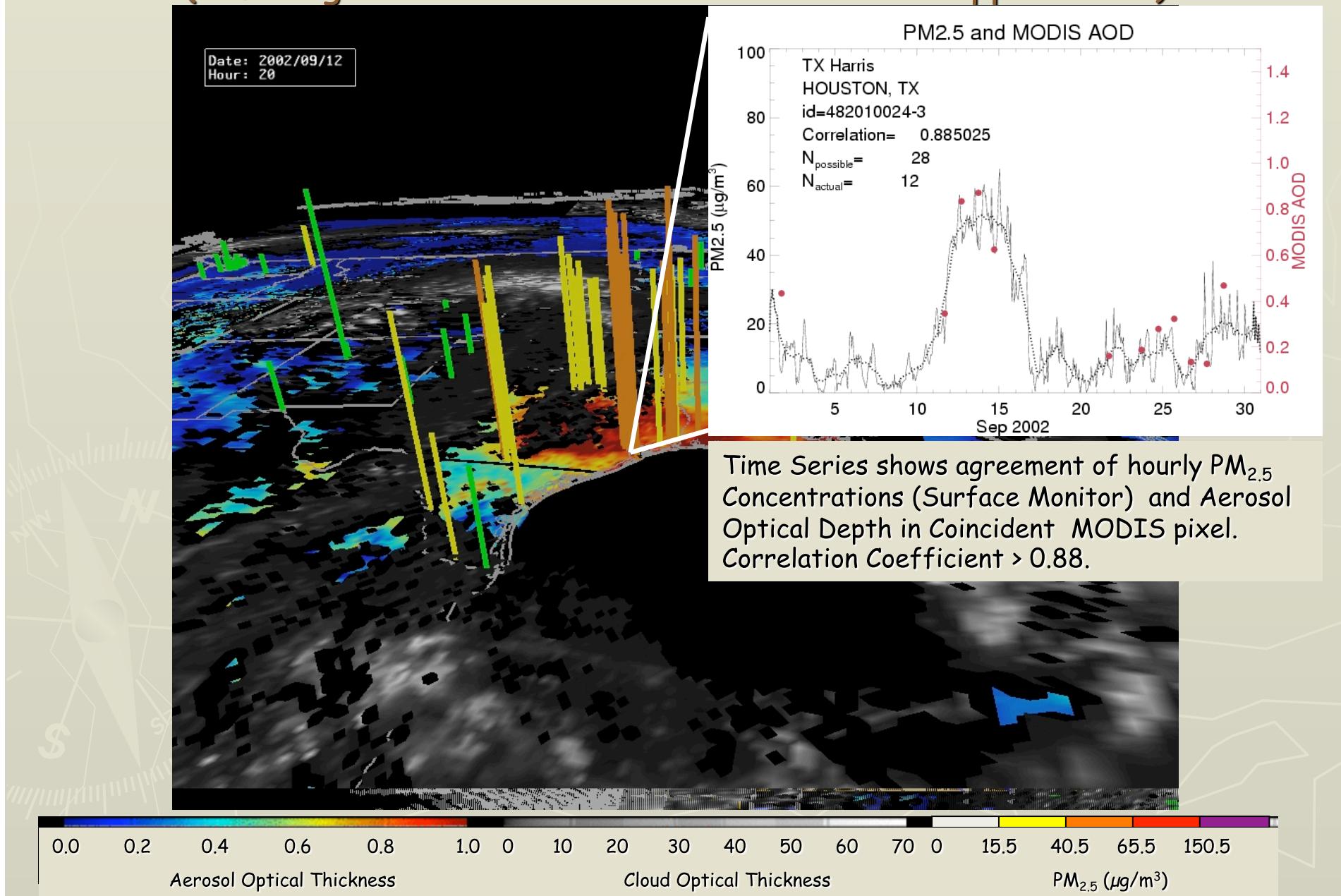
Aqua/MODIS Aerosol Optical Thickness: Composite of Dark Vegetation & Deep Blue Products



Aqua/MODIS Aerosol Optical Thickness: Composite of Dark Vegetation & Deep Blue Products



Air Quality from Ground ($\text{PM}_{2.5}$) and Satellite (MODIS) (Infusing Satellite Data into Environmental Applications)



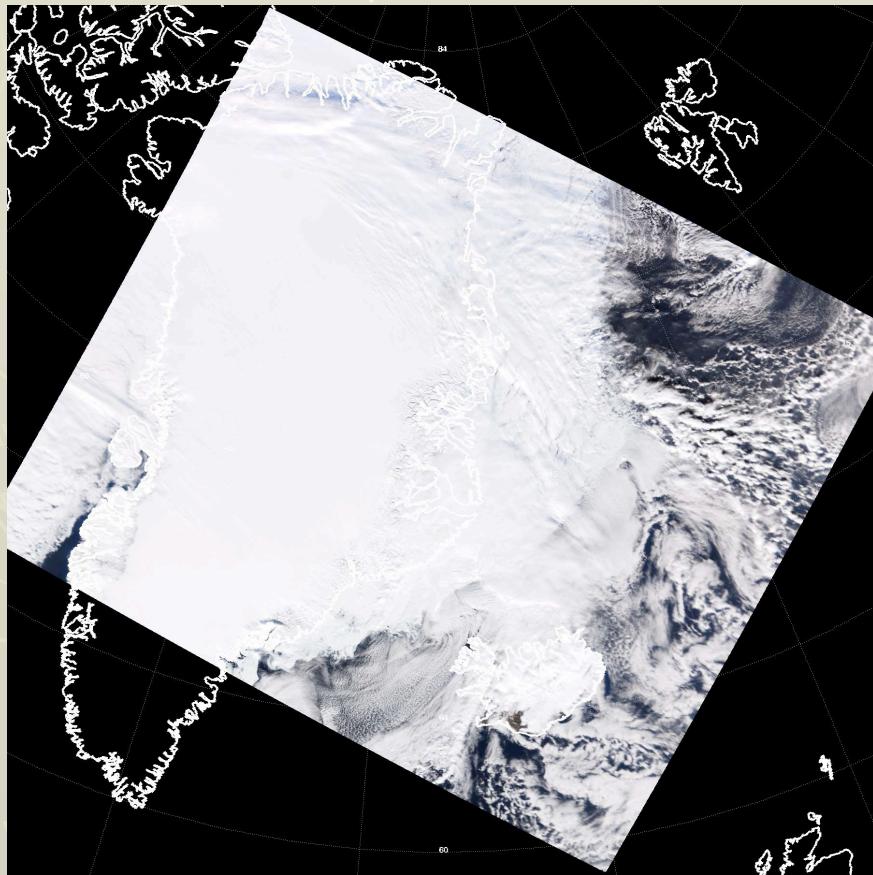
MODIS Cloud Products

- Pixel-level (level-2) products
 - Cloud mask for distinguishing clear sky from clouds
 - Cloud radiative and microphysical properties
 - ✓ Cloud top pressure, temperature, and effective emissivity
 - ✓ Cloud optical thickness, thermodynamic phase, and effective radius
 - ✓ Thin cirrus reflectance in the visible
- Gridded time-averaged (level-3) atmosphere product
 - Daily
 - Eight-day
 - Monthly
 - ✓ $1^\circ \times 1^\circ$ equal angle grid
 - ✓ Mean, standard deviation, marginal probability density function, joint probability density function

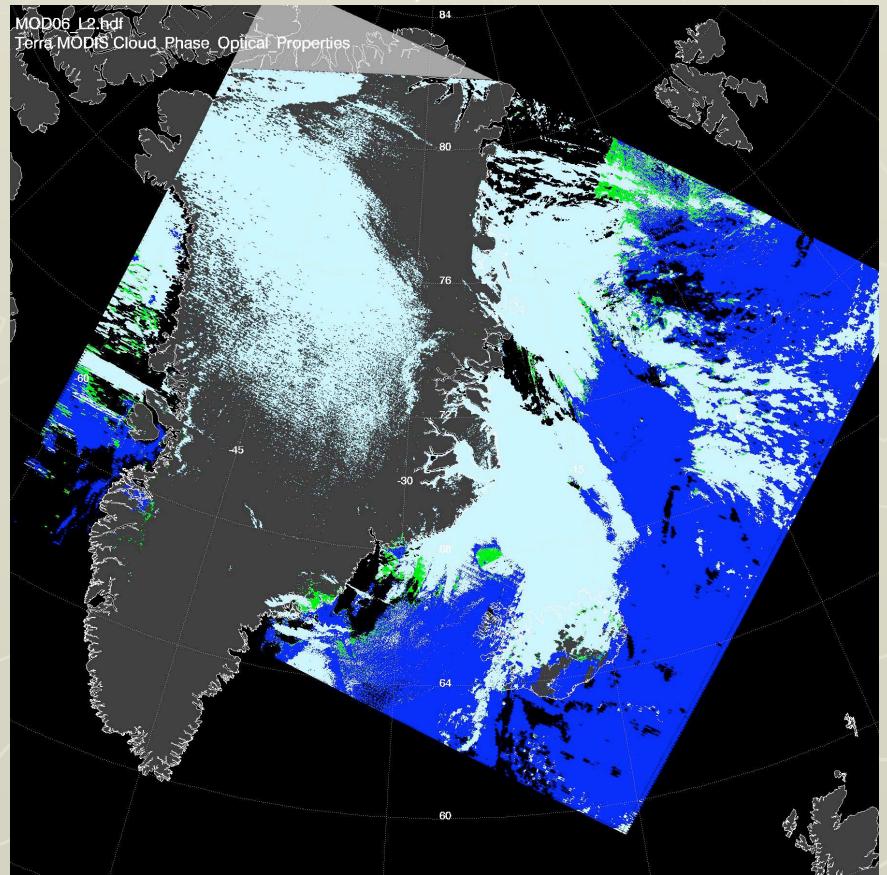
Terra/MODIS Cloud Thermodynamic Phase

(M. D. King, S. Platnick, J. Riedi et al. - NASA GSFC, U. Lille)

True Color Composite (0.65, 0.56, 0.47)



Thermodynamic Phase

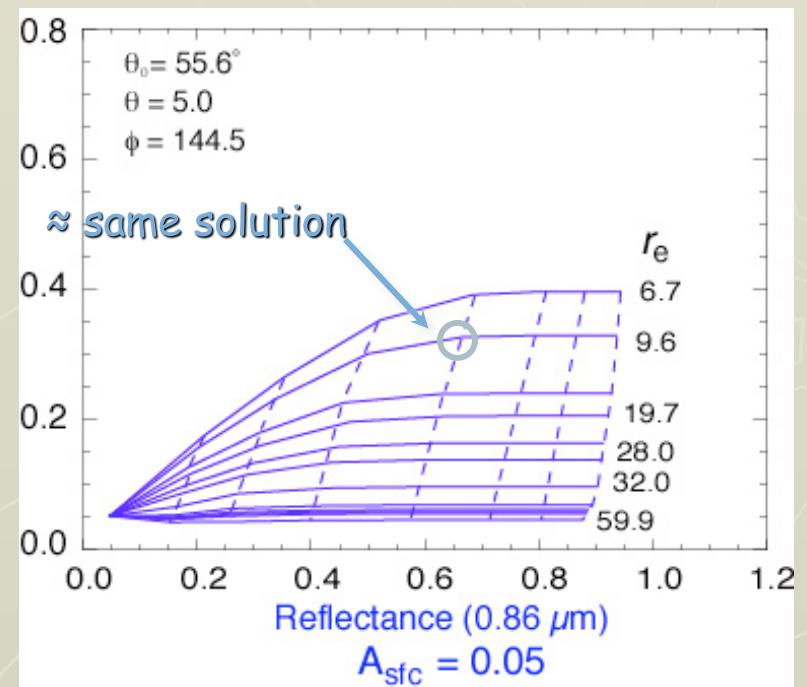
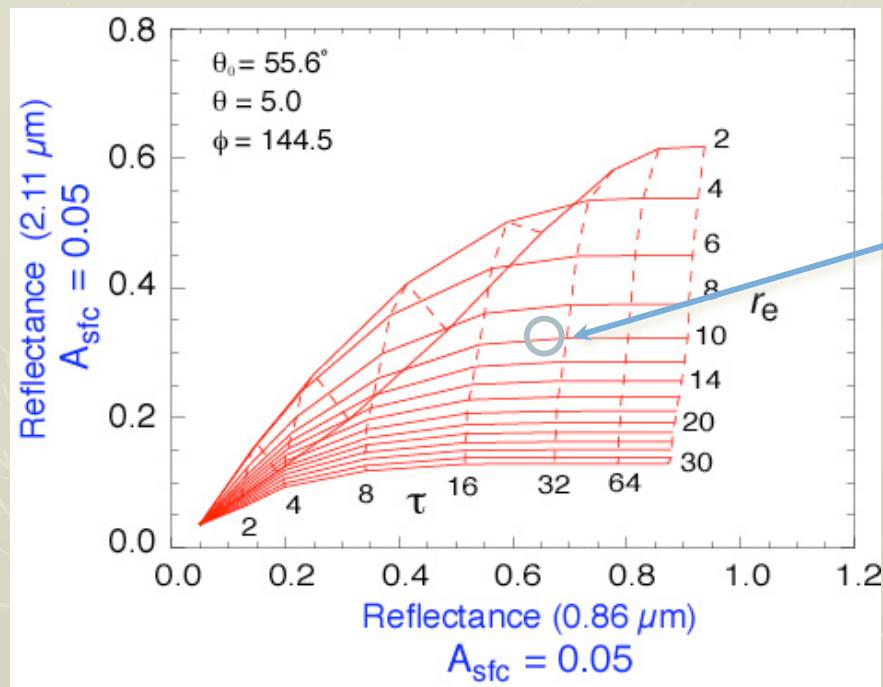


Clear Sky Liquid water Ice Uncertain

Collection 5

Cloud Optical & Microphysical Retrievals

Retrieval space examples



Liquid water cloud
ocean surface

Ice cloud
ocean surface

Based on Nakajima and King (1990) algorithm

Ice Cloud Size Distributions

(based on airborne *in situ* field campaigns over 20 years)

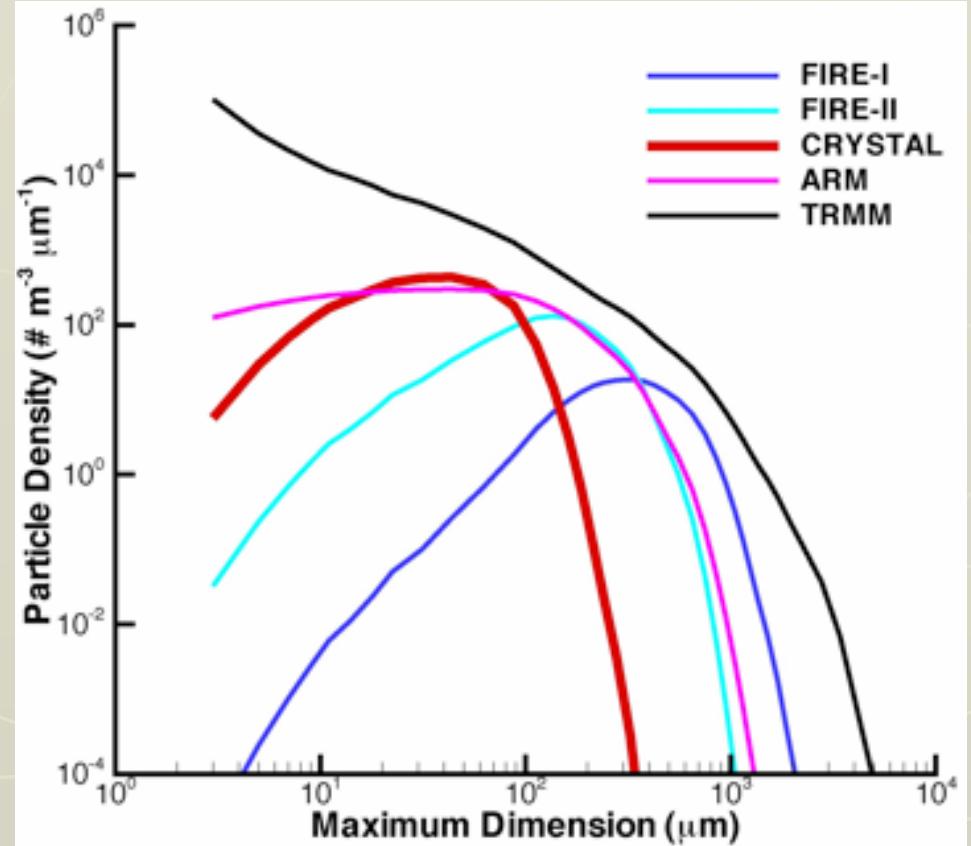
Collection 5

➤ Ice Clouds

- 1100 size distributions analyzed from field campaigns in the midlatitudes, tropics, and subtropics
- Size distribution characterized by 45 size bins



Baum et al. (2005)



Ice Crystal Habits used in Light Scattering Calculations

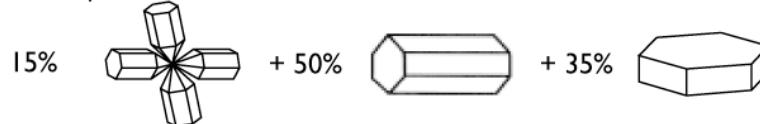
habits/shapes

MODIS cirrus cloud microphysical model

$D < 60 \mu\text{m}$:



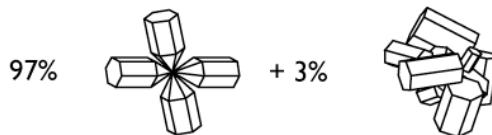
$60 \mu\text{m} < D < 1000 \mu\text{m}$:



$1000 \mu\text{m} < D < 2500 \mu\text{m}$:

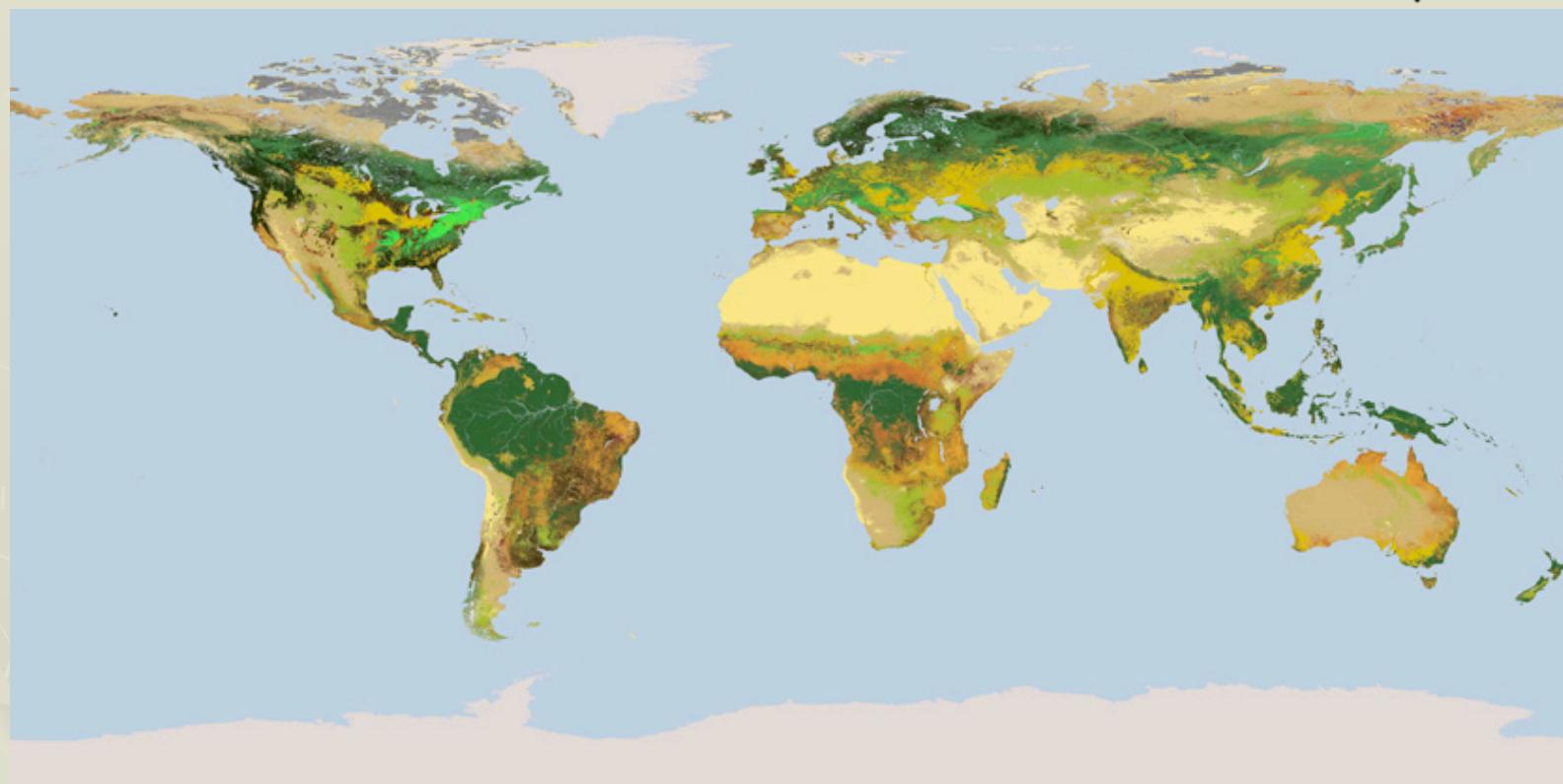


$2500 \mu\text{m} < D < 9500 \mu\text{m}$:



MODIS Land Cover Classification

(M. A. Friedl, A. H. Strahler et al. - Boston University)



- 0 Water
- 1 Evergreen Needleleaf Forest
- 2 Evergreen Broadleaf Forest
- 3 Deciduous Needleleaf Forest
- 4 Deciduous Broadleaf Forest
- 5 Mixed Forests

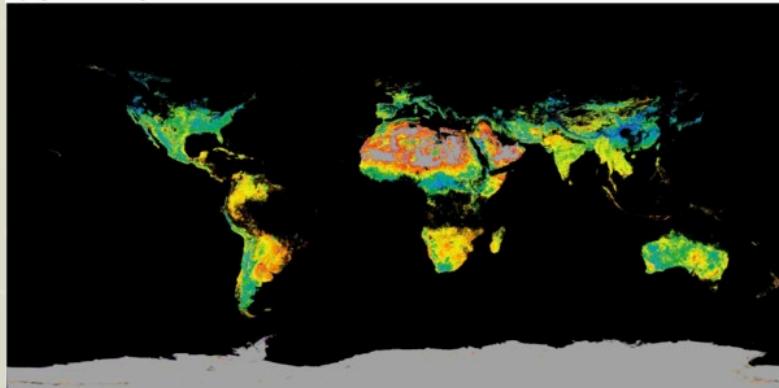
- 6 Closed Shrublands
- 7 Open Shrublands
- 8 Woody Savannas
- 9 Savannas
- 10 Grasslands
- 11 Permanent Wetlands

- 12 Croplands
- 13 Urban and Built-Up
- 14 Cropland/Natural Veg. Mosaic
- 15 Snow and Ice
- 16 Barren or Sparsely Vegetated
- 17 Tundra

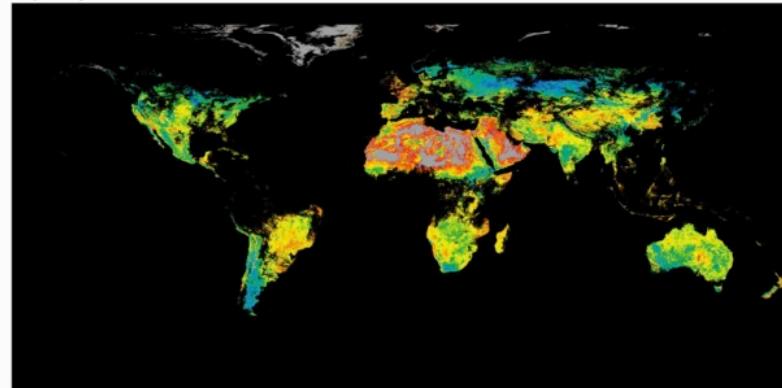
Conditioned MODIS Spectral Albedo Maps

(C. B. Schaaf, F. Gao, A. H. Strahler - Boston University)

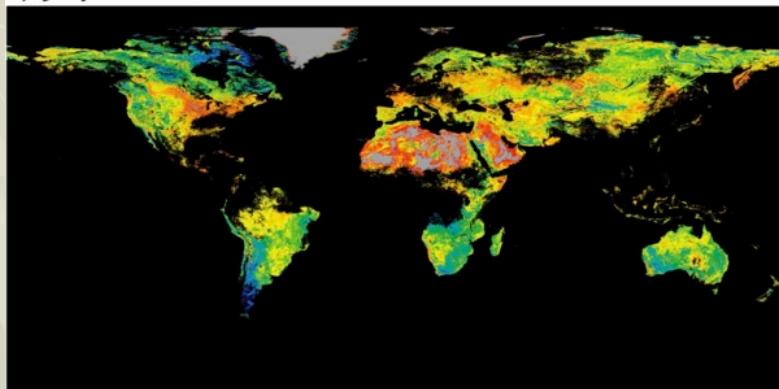
a) January 1-16, 2002



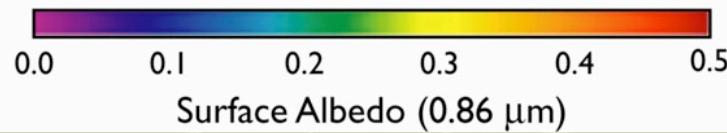
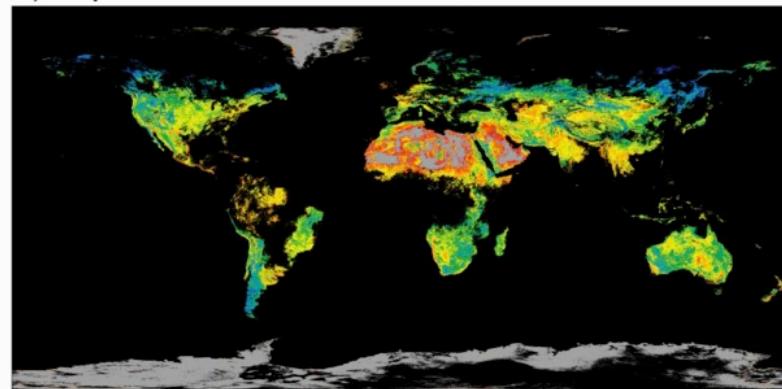
b) April 3-18, 2002



c) July 12-27, 2002



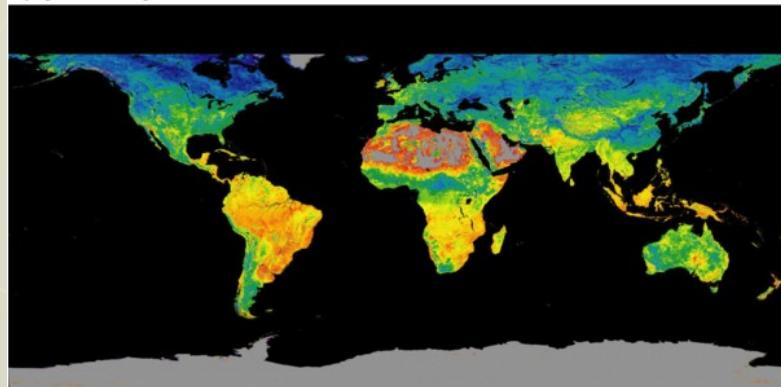
d) September 30-October 14, 2002



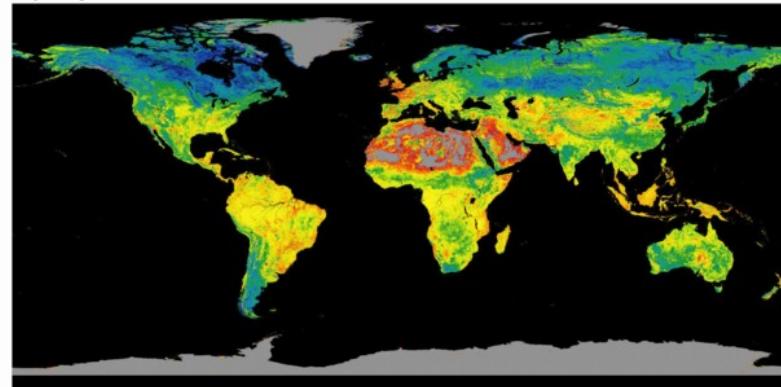
Spatially Complete Spectral Albedo Maps

(E. G. Moody, M. D. King, S. Platnick, C. B. Schaaf, F. Gao - GSFC, BU)

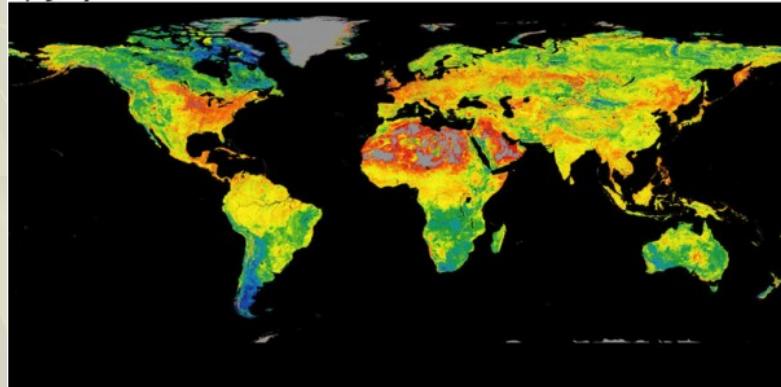
a) January 1-16, 2002



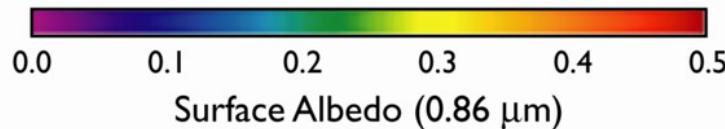
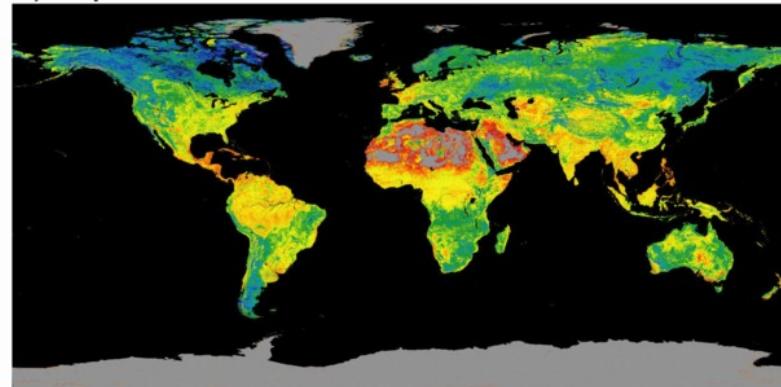
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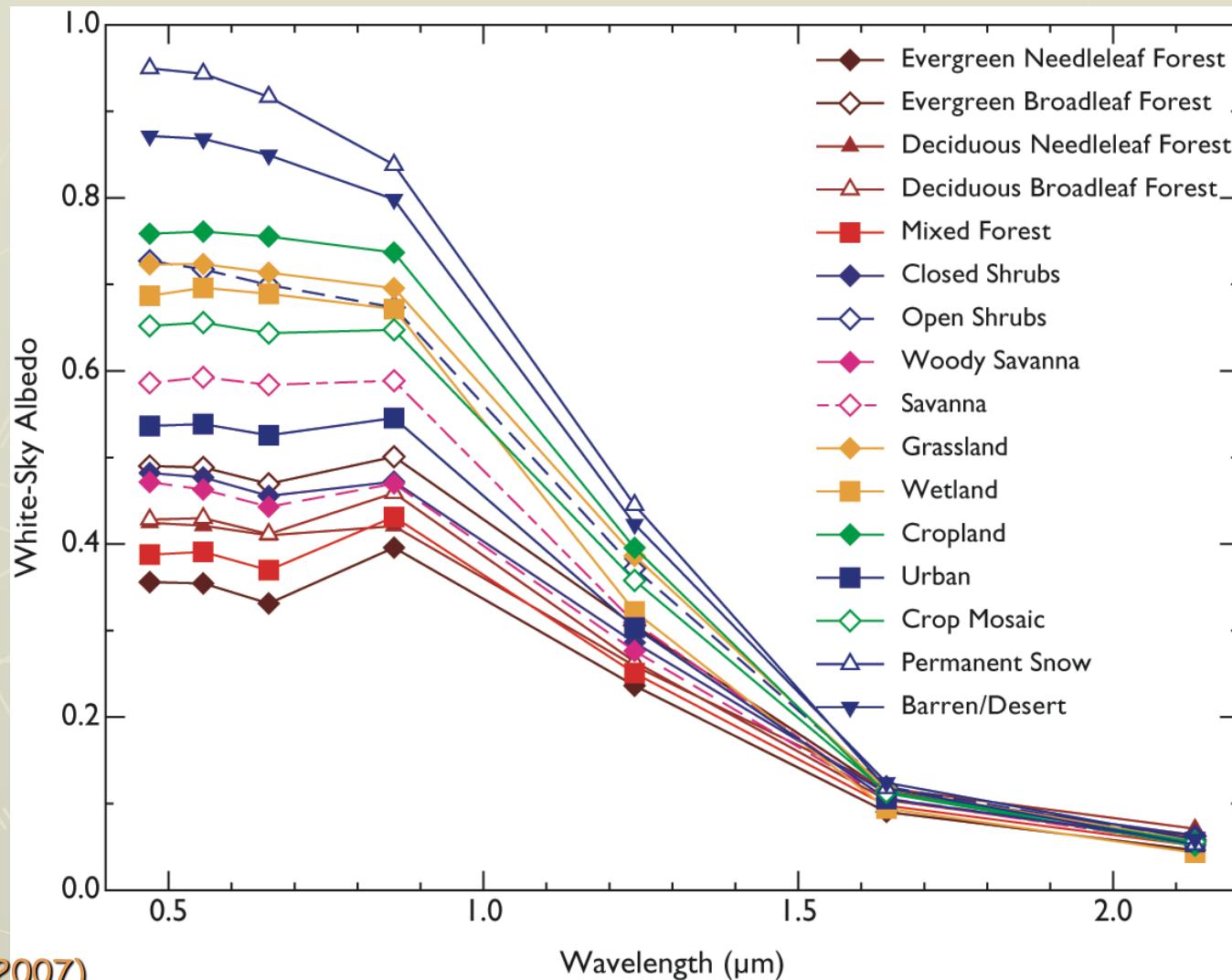


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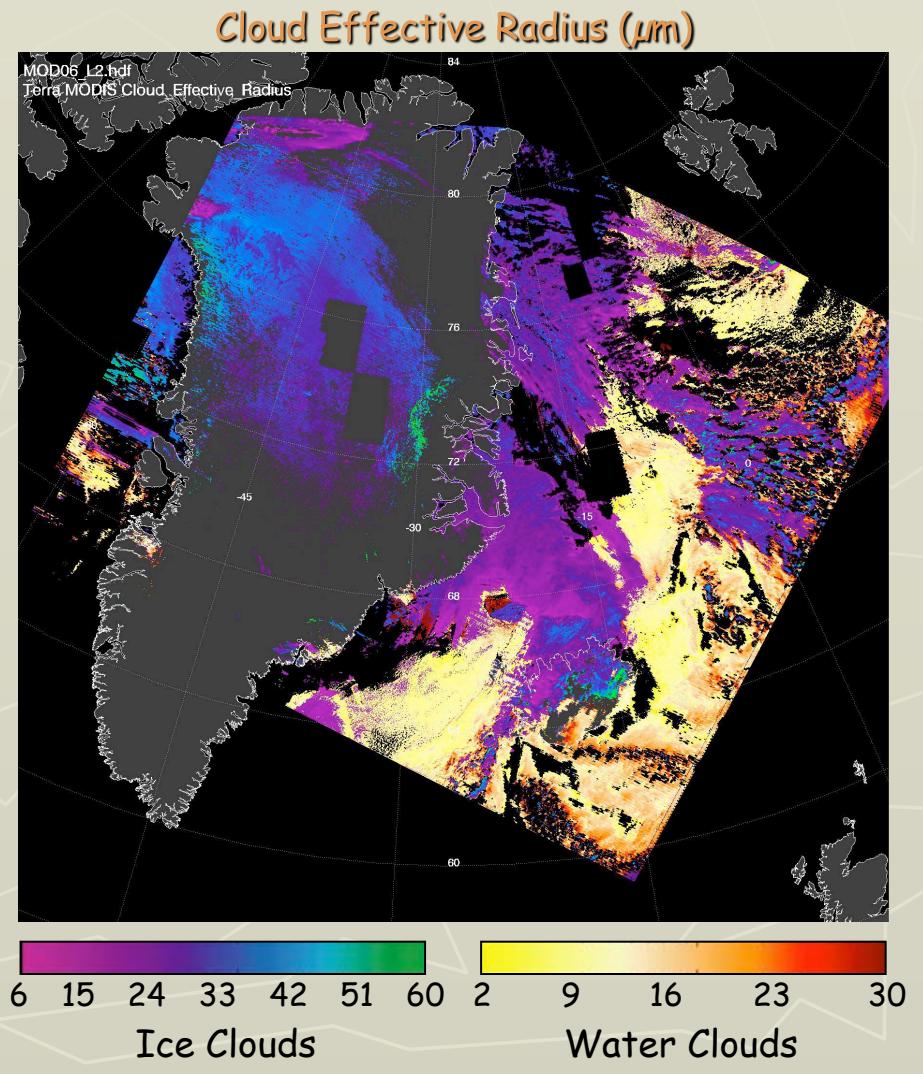
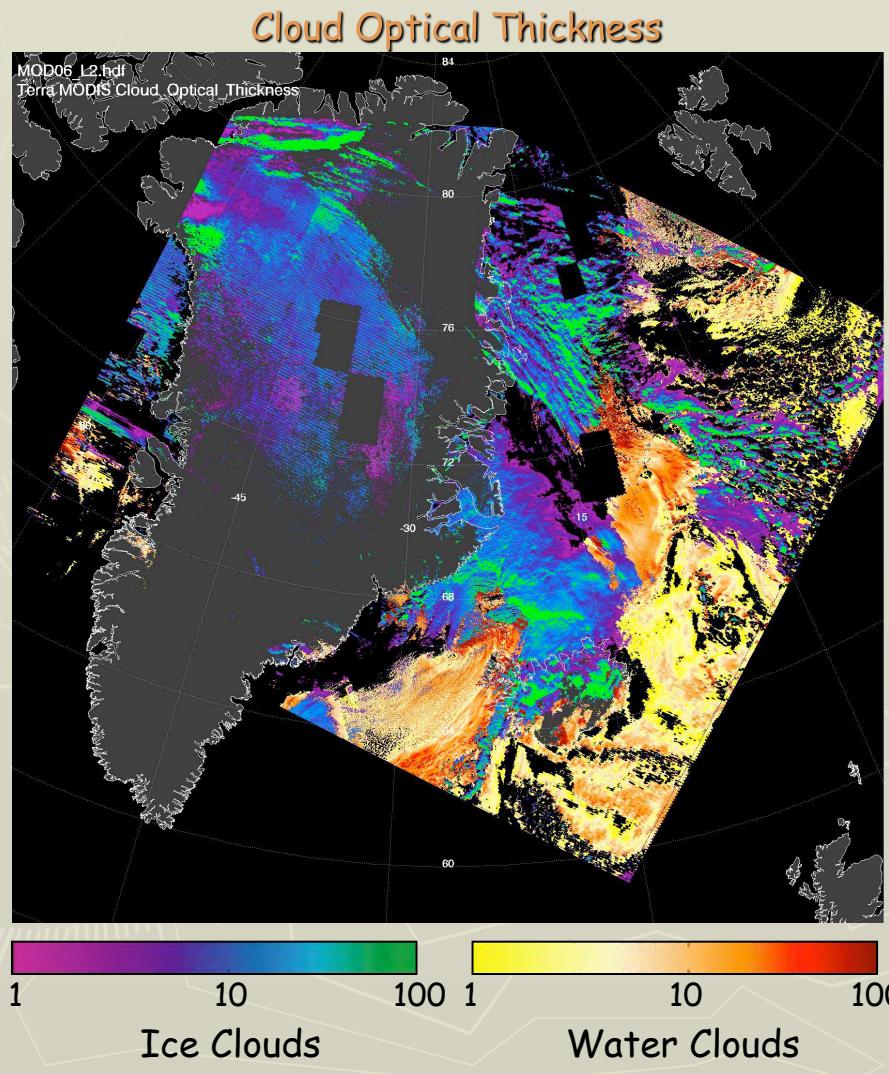
Snow Albedo by IGBP Ecosystem

Northern Hemisphere Multiyear Average (2000-2004)



Cloud Optical Thickness and Effective Radius

(M. D. King, S. Platnick - NASA GSFC)

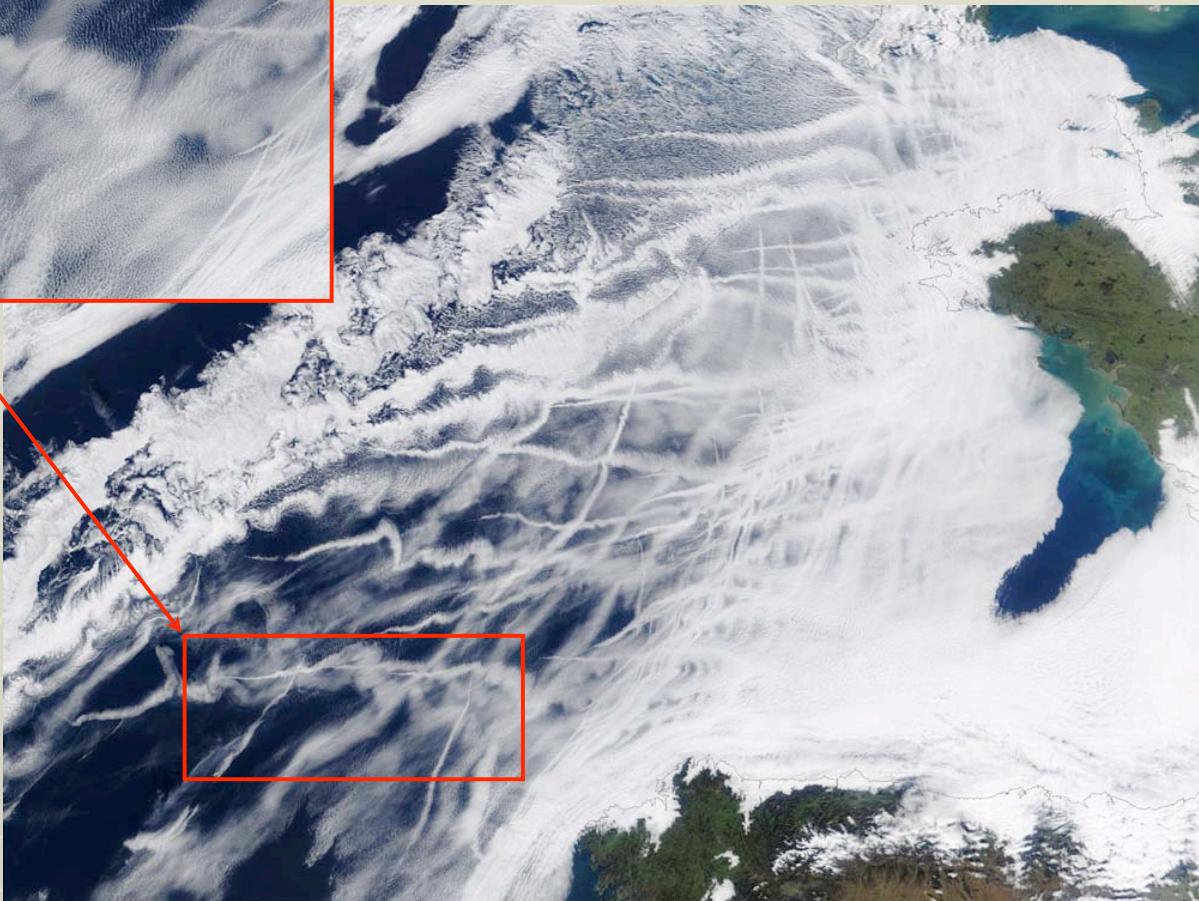


Ship Tracks

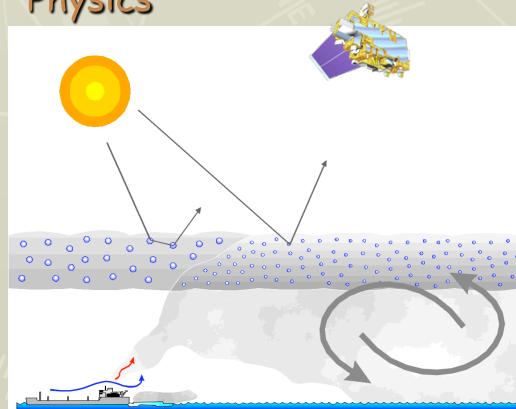
(S. Platnick - NASA GSFC)



Terra/MODIS True color composite



Physics

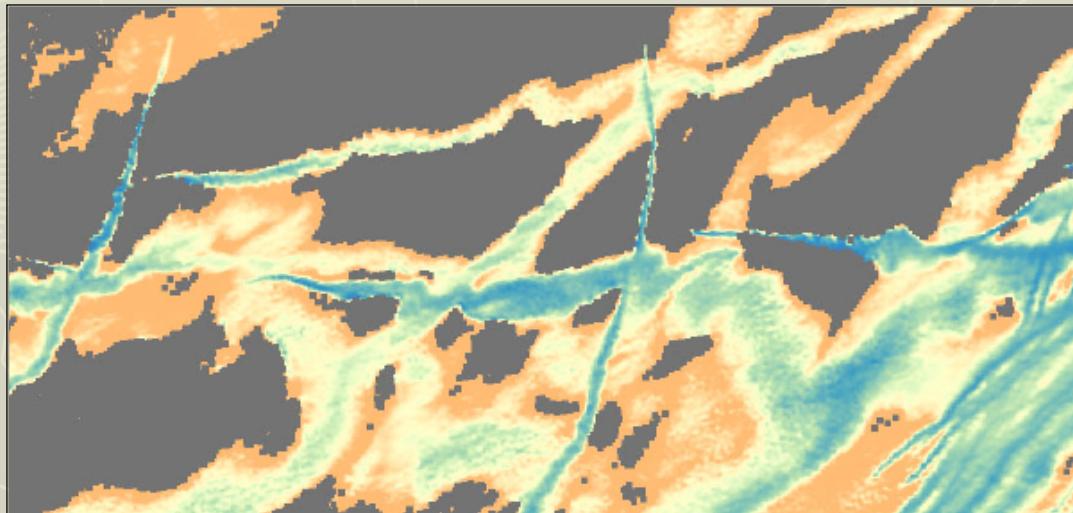
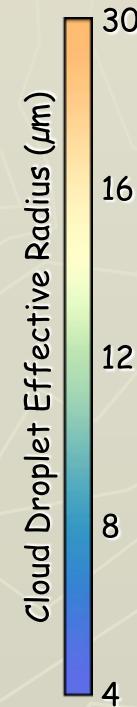


Platnick (2007)

January 27, 2003

Aerosol Cloud Interaction

Aqua/MODIS Retrievals



Platnick (2007)

January 27, 2003

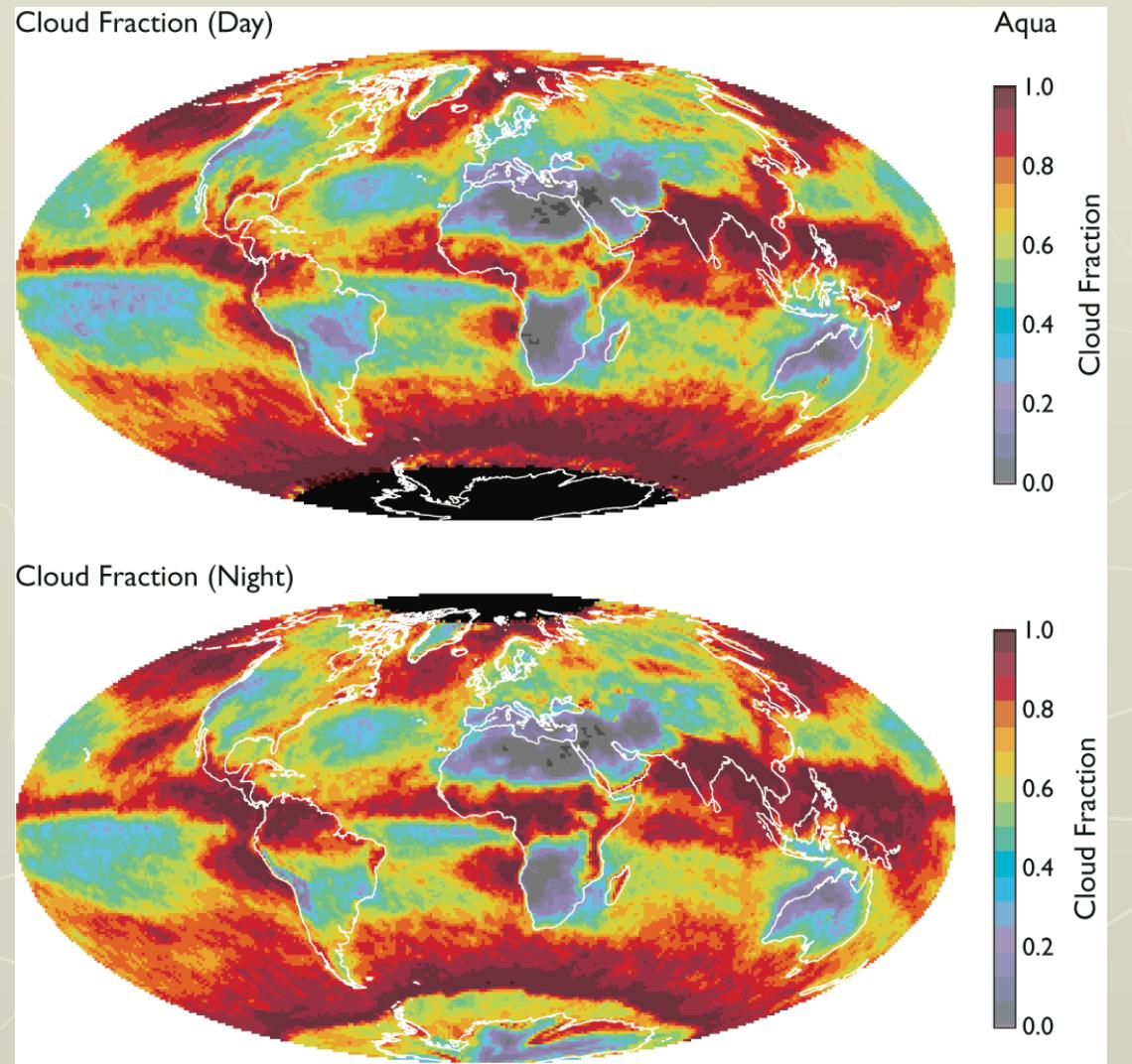
Monthly Mean Cloud Fraction

(S. A. Ackerman, R. A. Frey et al. - Univ. Wisconsin)

Aqua/MODIS

- Cloud fraction similar during day and night
 - High cloud amount
 - ✓ Roaring 40s
 - ✓ ITCZ
 - ✓ North Atlantic
 - ✓ Indonesia and western tropical Pacific
 - Low cloud amount
 - ✓ Subtropical gyres over the ocean
 - ✓ Deserts
 - ✓ Antarctica
 - ✓ Greenland

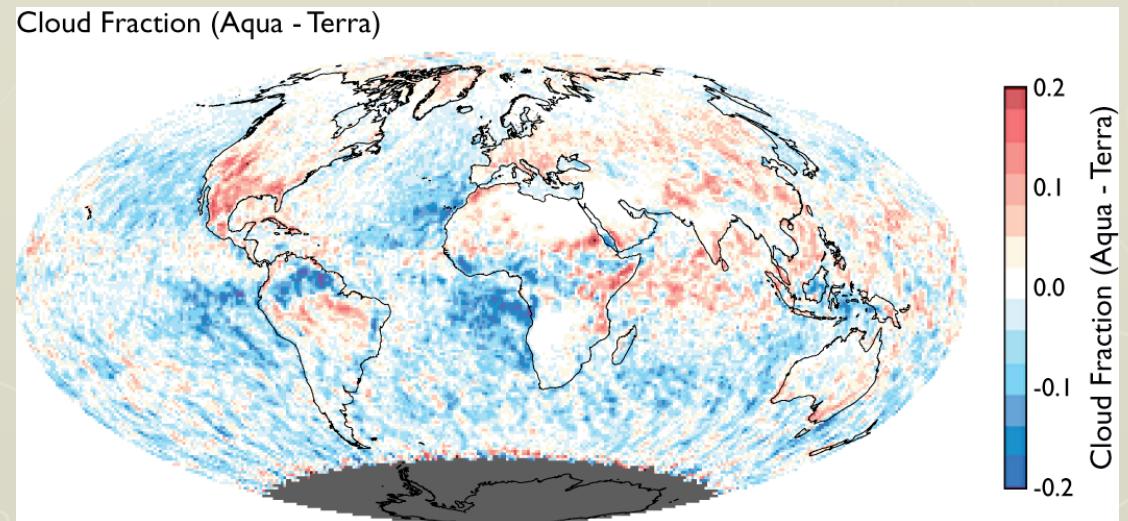
July 2006



Aqua Cloud Fraction - Terra Cloud Fraction

(M. D. King, S. Platnick et al. - NASA GSFC)

- Terra
 - Higher over oceans than land
 - ✓ Marine stratocumulus
- Aqua
 - Higher over land than ocean
 - ✓ Interior continents
 - ✓ Desert southwestern US
 - ✓ Australia
 - Higher over ocean than land
 - ✓ Northern Indian Ocean

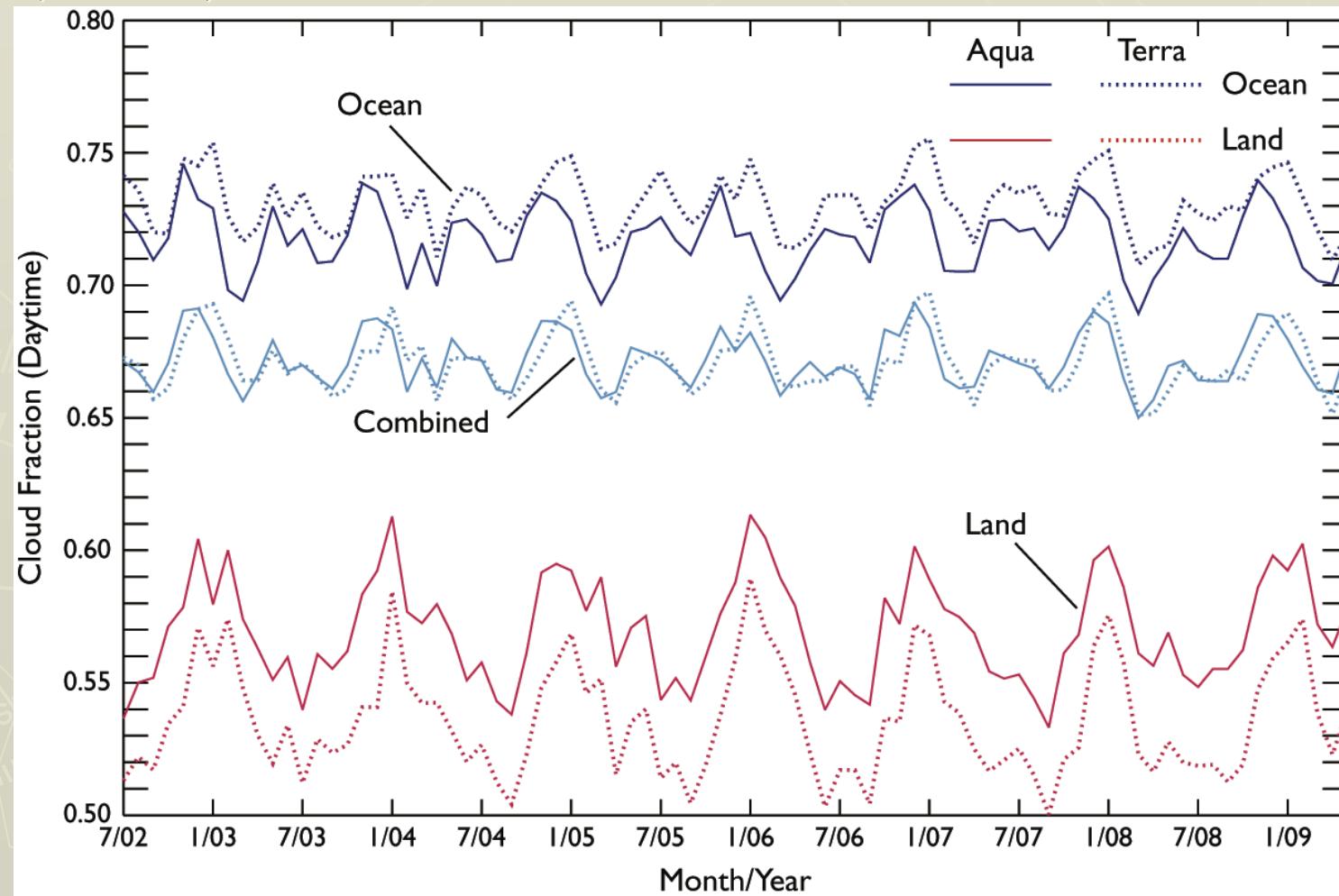


July 2006

Time Series of Cloud Fraction during the Daytime

(M. D. King, S. Platnick et al. - NASA GSFC)

July 2002 - April 2009



Monthly Mean Cloud Top Properties

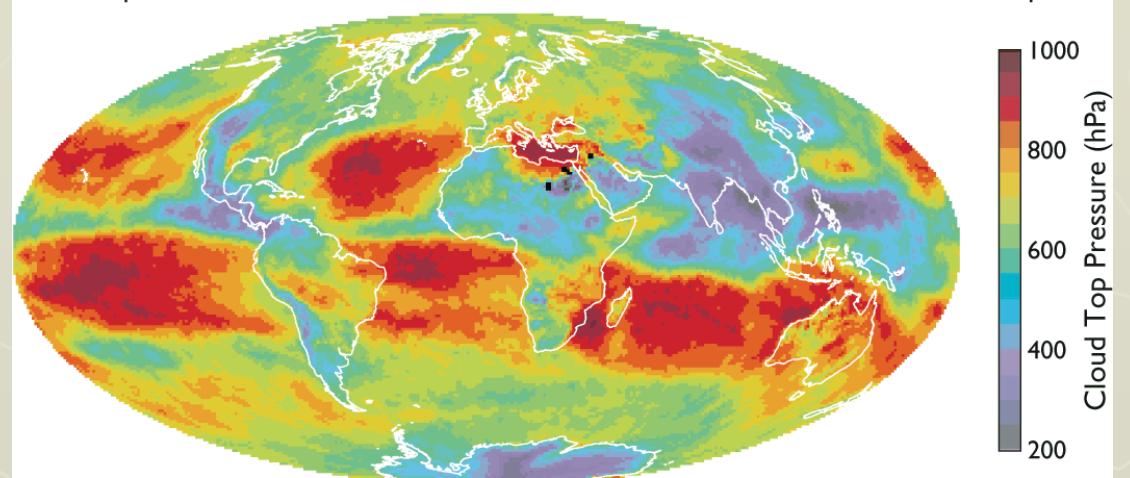
(W. P. Menzel, R. A. Frey et al. - Univ. Wisconsin)

July 2006

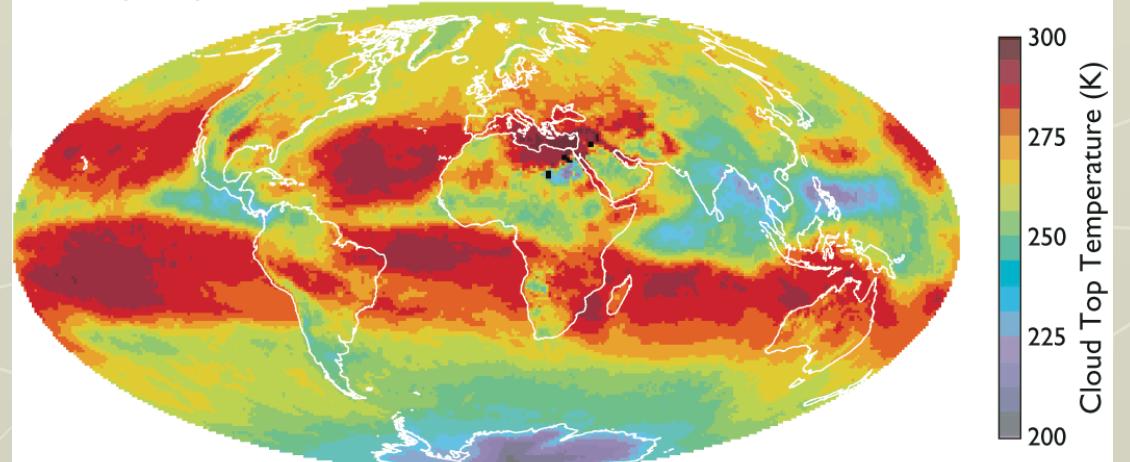
Aqua

- Liquid water clouds
 - Marine stratocumulus regions
 - ✓ Angola/Namibia
 - ✓ Peru/Ecuador
 - ✓ California/Mexico
- Ice clouds
 - Tropics
 - ✓ Indonesia & western tropical Pacific
 - ✓ ITCZ
 - Roaring 40s

Cloud Top Pressure



Cloud Top Temperature



Monthly Mean Cloud Fraction by Phase

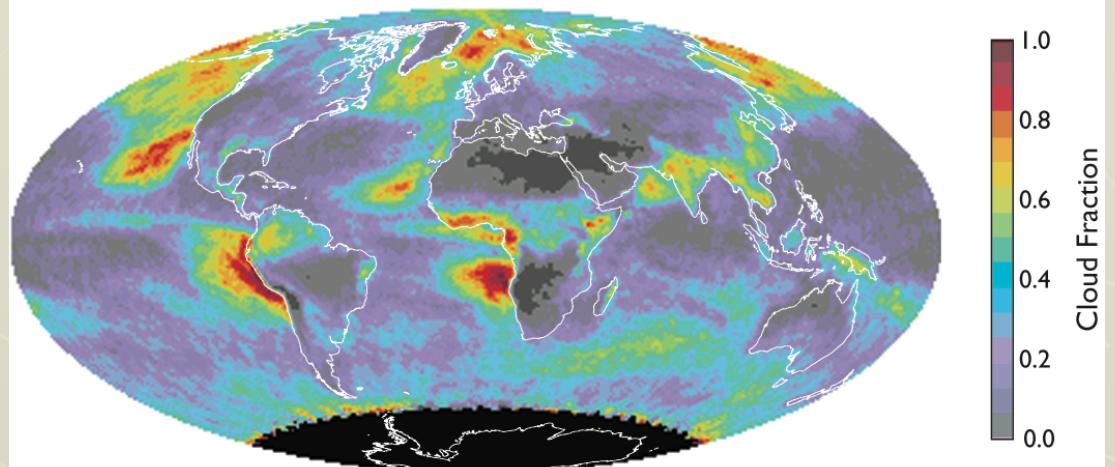
(M. D. King, S. Platnick et al. - NASA GSFC)

July 2006

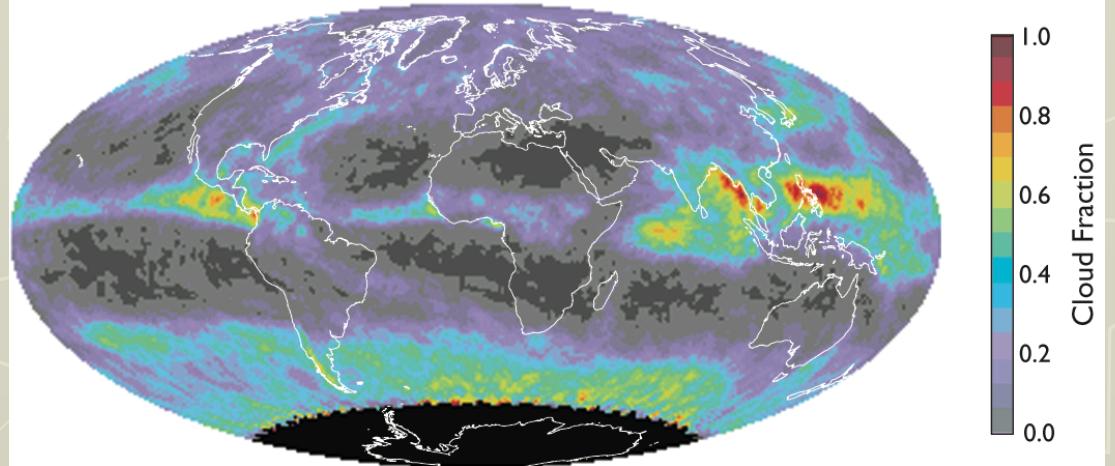
Terra

- Liquid water clouds
 - Marine stratocumulus regions
 - ✓ Angola/Namibia
 - ✓ Peru/Ecuador
 - ✓ California/Mexico
- Ice clouds
 - Tropics
 - ✓ Indonesia & western tropical Pacific
 - ✓ ITCZ
 - Roaring 40s

Cloud Fraction (Liquid Water)



Cloud Fraction (Ice)



Monthly Mean Cloud Effective Radius

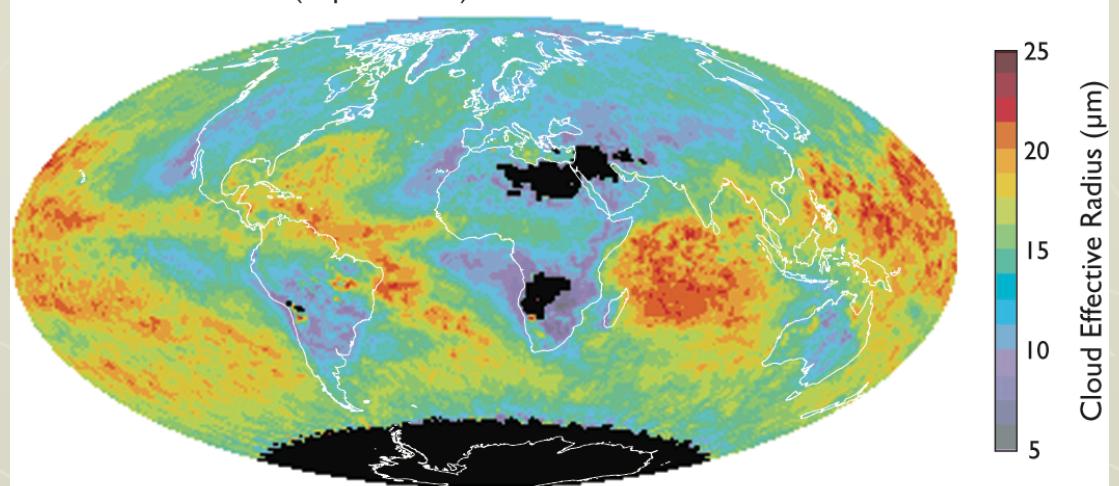
(M. D. King, S. Platnick et al. - NASA GSFC)

July 2006

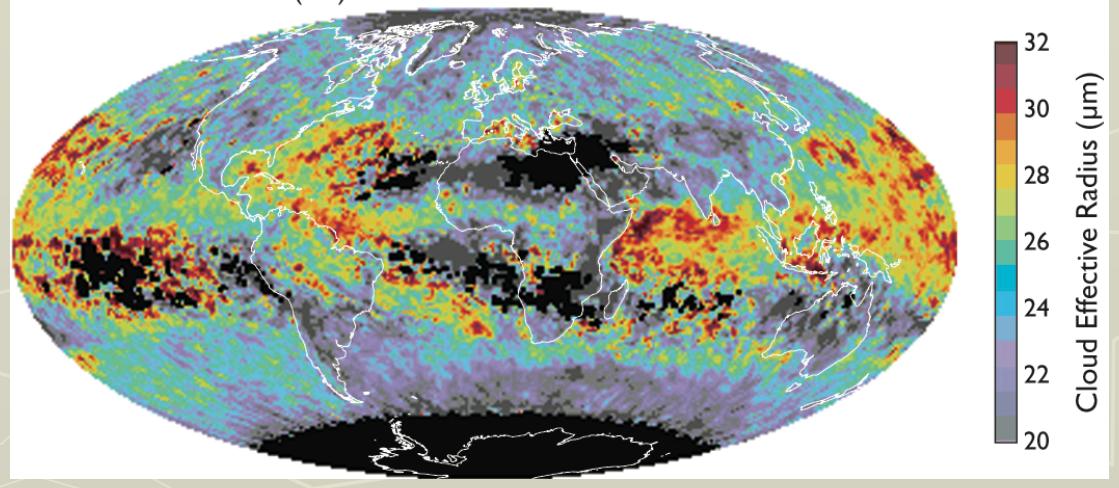
Terra (QA Mean)

- Liquid water clouds
 - Larger drops in SH than NH
 - Larger drops over ocean than land
 - ✓ Due to cloud condensation nuclei (aerosols)
- Ice clouds
 - Larger in tropics than high latitudes
 - ✓ Anvils
 - Small ice crystals at top of deep convection

Cloud Effective Radius (Liquid Water)



Cloud Effective Radius (Ice)

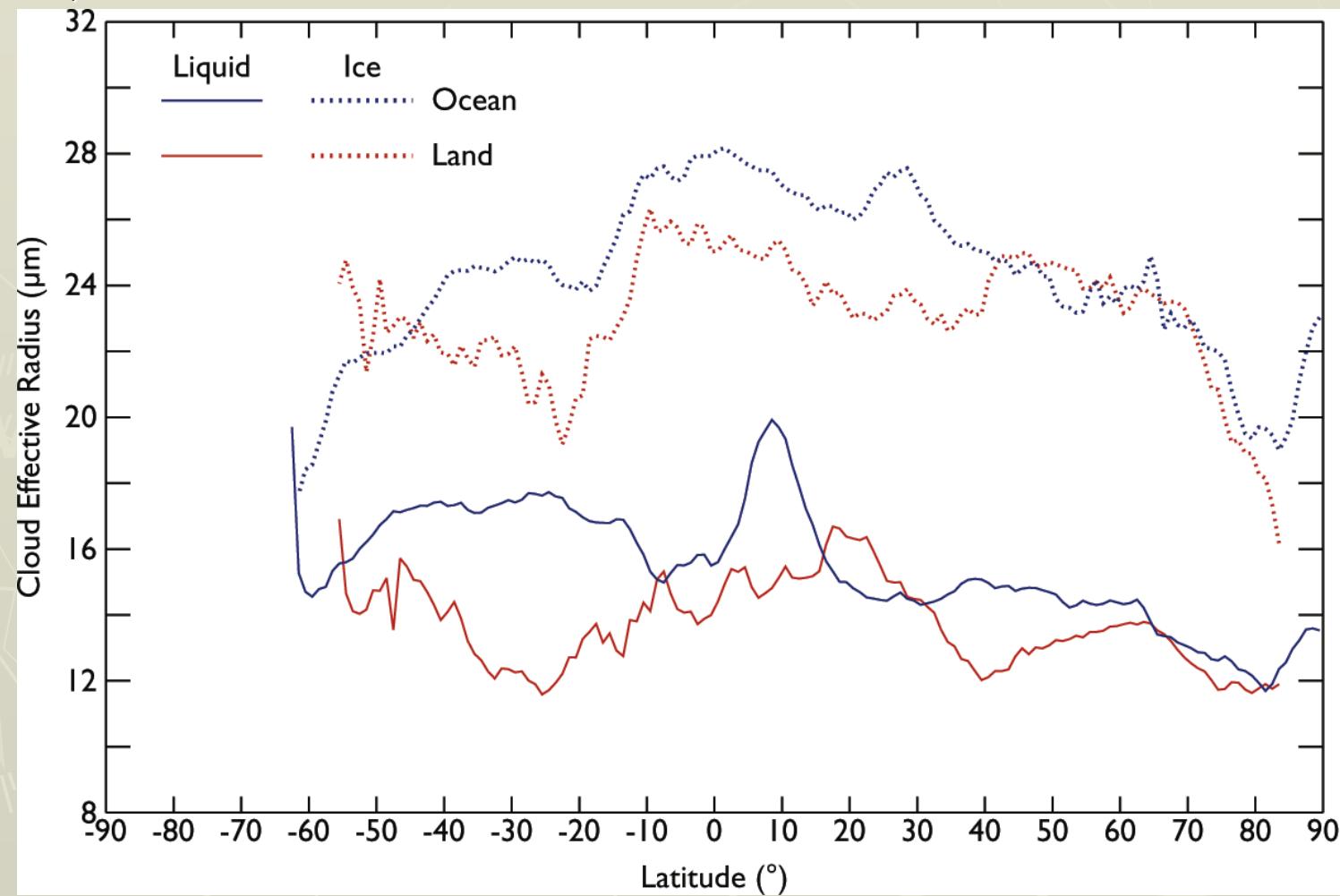


Zonal Mean Cloud Effective Radius

(M. D. King, S. Platnick et al. - NASA GSFC)

July 2006

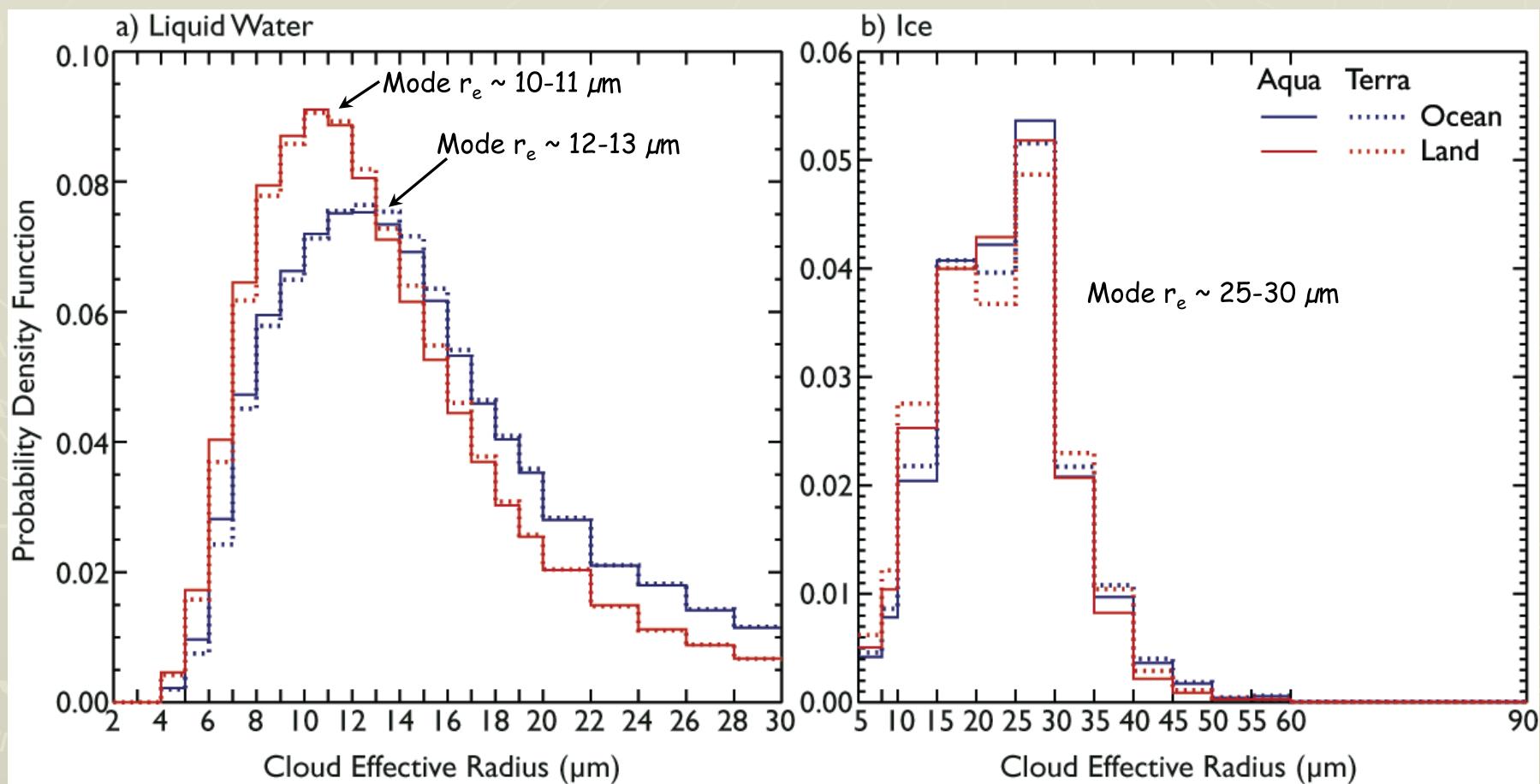
Terra



Probability Distribution of Cloud Effective Radius

(M. D. King, S. Platnick et al. - NASA GSFC)

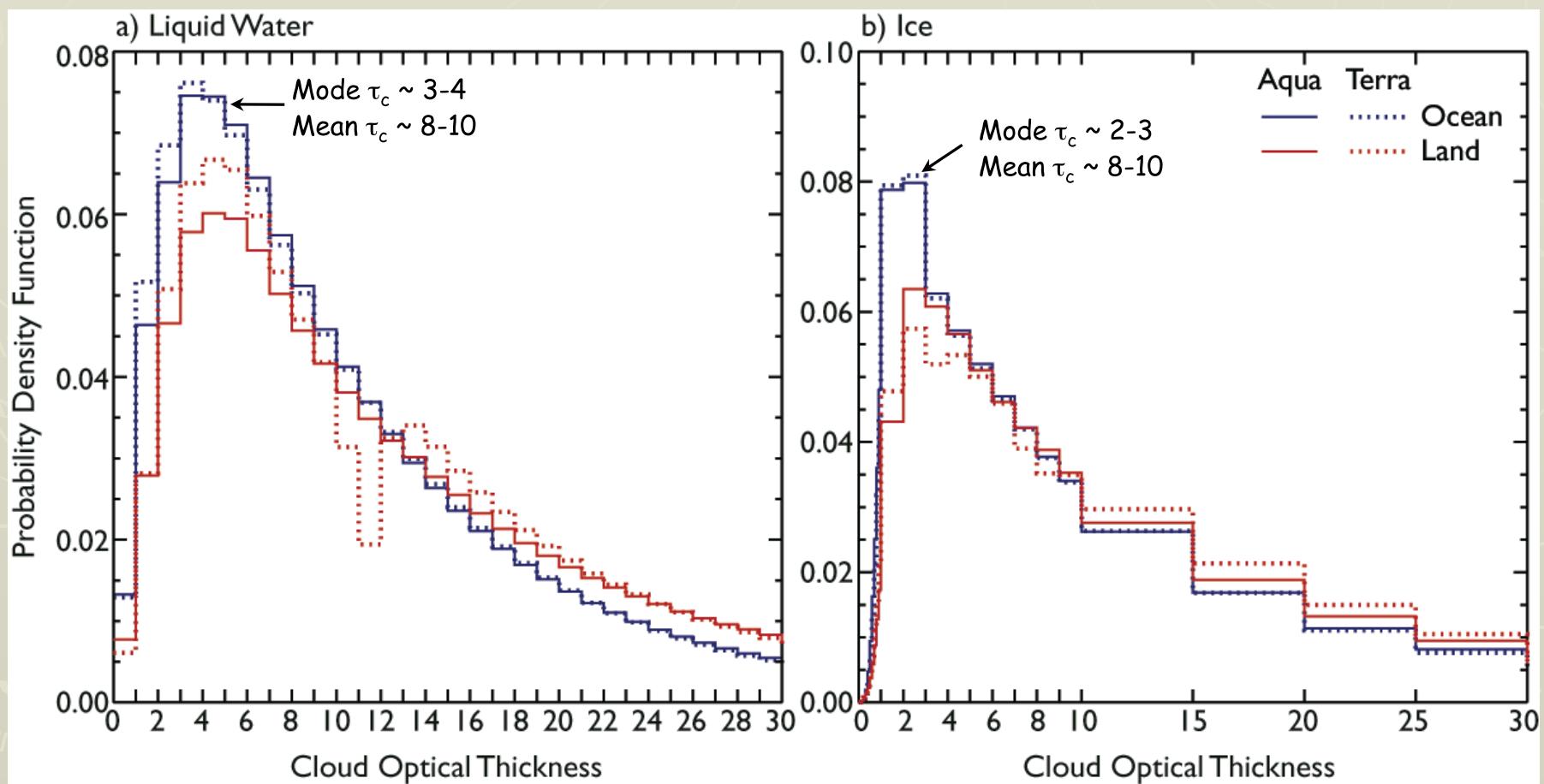
July 2006



Probability Distribution of Cloud Optical Thickness

(M. D. King, S. Platnick et al. - NASA GSFC)

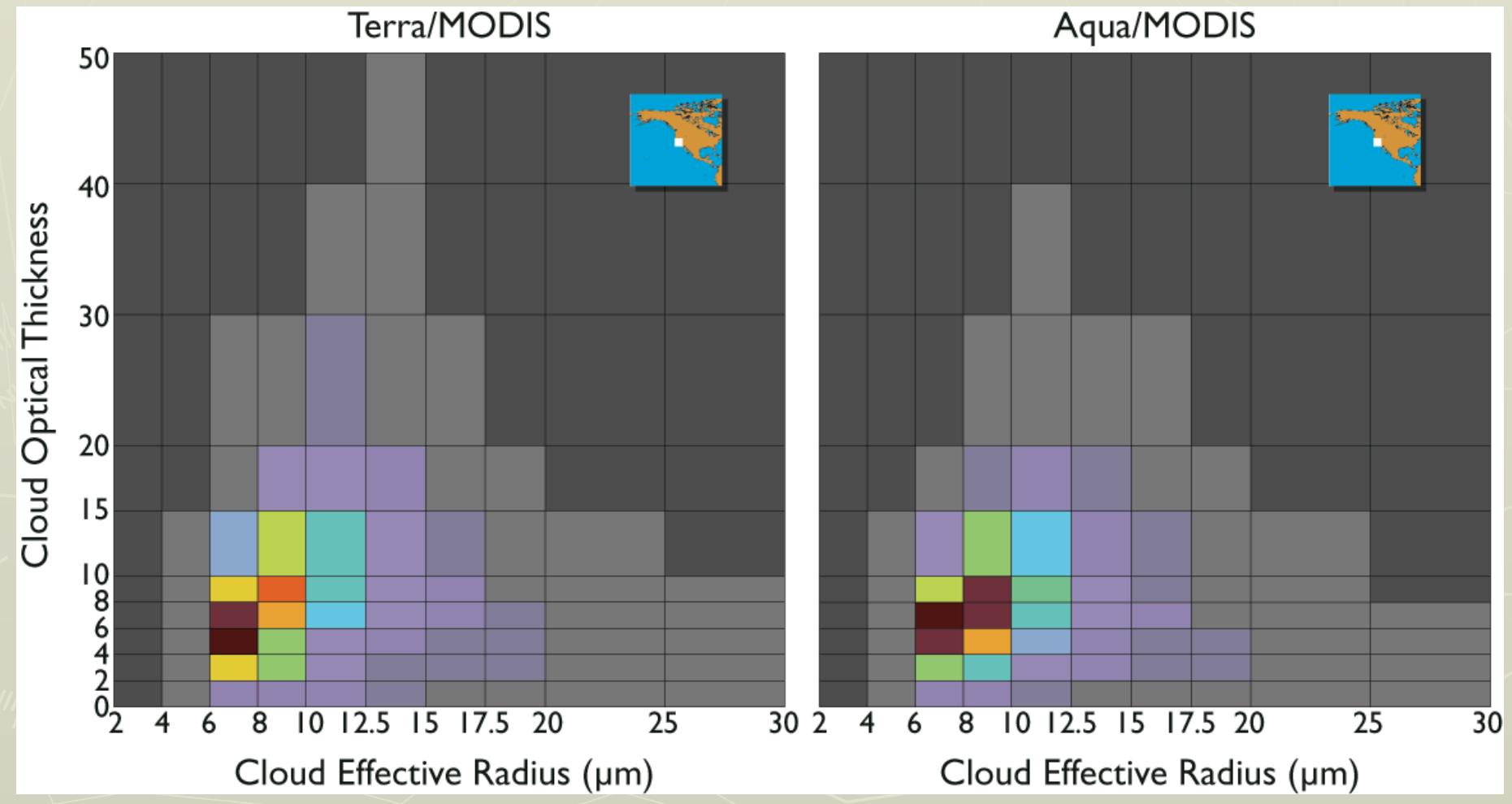
July 2006



MODIS τ_c vs r_e Joint Histograms

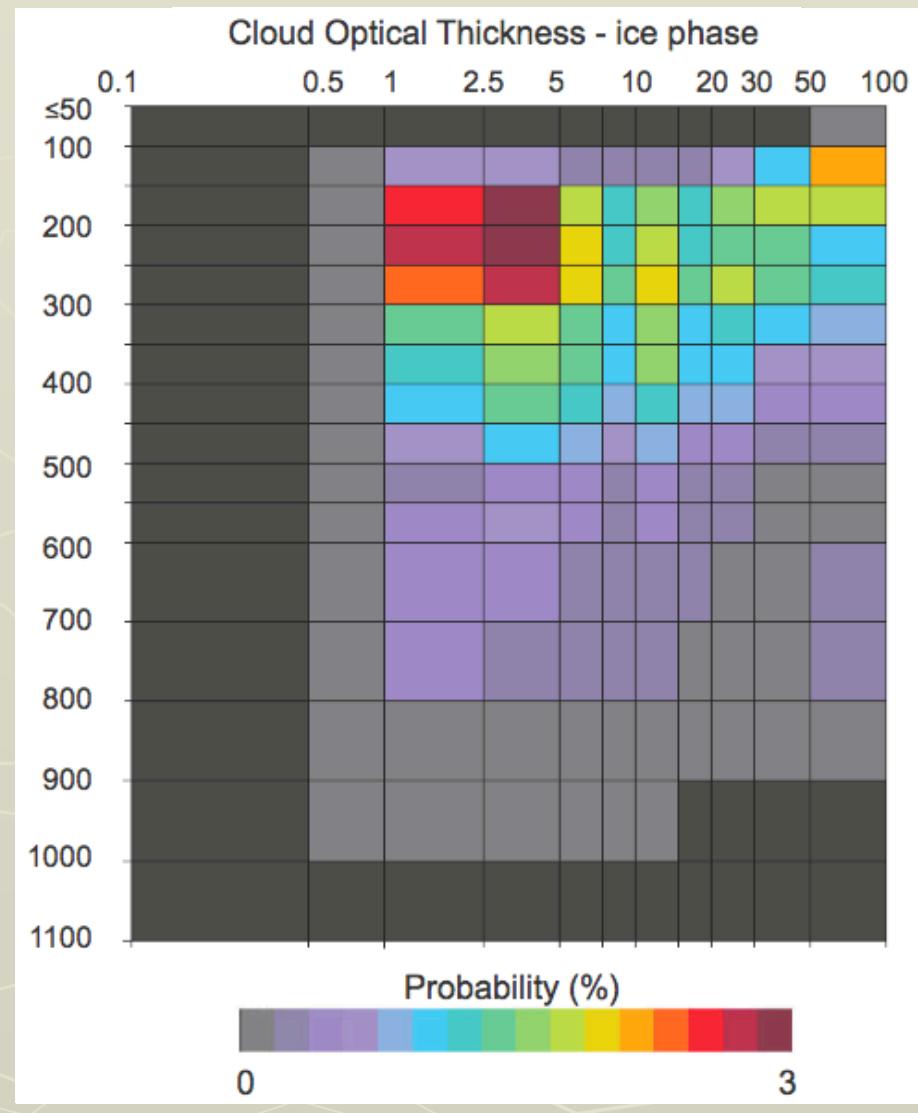
Liquid Water Clouds over Ocean

32°-40°N, 117°-125°W
July 2006



MODIS and ISCCP-like τ_c vs p_c Joint Histograms

50°N-50°S
Terra
August 2001



Summary and Conclusions

➤ Aerosol optical & microphysical properties

- Advent of well-calibrated radiometers since 1999 allows quantitative assessments of aerosol optical thickness and related properties over both ocean and land (MODIS, MISR)
 - ✓ Aerosol spatial and temporal variation
 - » Interannual variation associated with biomass burning and climate variations
 - » Urban-industrial aerosol optical thickness twice as high in India and China as US and western Europe
 - » Dust sources identified worldwide
 - Bodele Depression (Chad) and Taklimakan Desert (China) the world's largest source regions
 - ✓ Aerosol over land determined using dense dark vegetation and bright-reflecting surfaces (MODIS) and multiangle views (MISR)
 - » Aerosol injection height (MISR)
 - » Aerosol absorption for dust (MODIS Deep Blue algorithm)
 - ✓ Fraction of fine mode aerosol (MODIS) and nonspherical particles (MISR) retrieved for first time (experimental)
 - ✓ Applications to Air Quality Monitoring demonstrated in partnership with EPA
 - Preliminary studies of aerosol/cloud interactions (difficult)

Summary and Conclusions

➤ Cloud properties

- Well-calibrated and spectrally broad MODIS sensor allows studies of cloud cover, cloud top properties, and cloud optical properties
 - ✓ Cloud fraction nearly the same during daytime and nighttime
 - » Higher over ocean than land
 - » Higher over land in afternoon and ocean in morning
 - » Global average of 66%-69%
 - Higher during northern winter
 - ✓ Cloud optical properties
 - » Separate for the first time liquid water vs ice clouds
 - Requires treatment of light scattering by nonspherical particles (ice)
 - » Effective radius of liquid water clouds higher over ocean than land
 - Mode radius is 10-11 μm over ocean and 12-13 μm over land, with long tail
 - » Nice example of aerosol/cloud interactions occurs in ship tracks
 - ✓ Joint probability density function of cloud optical, physical, and microphysical properties a good test for General Circulation Models
- Ready access to Web applications in last decade makes access to these results accessible to all